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A BEHAVIORAL SIMULATION MODEL OF FORECASTING AND PRODUCTION SCHEDULING IN A DATACOMMUNICATIONS COMPANY

by

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Abstract

The paper describes a behavioral simulation model of forecasting and production scheduling in a datacommunications company. The model allows you to think about the different 'players' whose choices and actions regulate orders and production. There are business planners (who provide forecasts), factory schedulers, expediters, customers and account executives. You step into their shoes. You examine their responsibilities, their goals and incentives and the sources of information that attract their attention -- all with the intention of understanding the logic behind their choices and actions. Then you stand back from the detail and, with the help of diagrams and simulations, you explore how the players interact and cooperate, and how the factory balances supply and demand.

INSIDE THE FACTORY

Imagine youself as the manager of a factory that produces workstations, PBXs, key systems and other datacommunications equipment. Your factory has been criticized recently for slow deliveries. The delivery interval of workstations ranges from six months to one year, much longer than major competitors. The problem is not improving. You begin searching for an explanation.

Many ideas come to mind. One could argue that the factory's long delivery intervals are due to errors in the sales forecast. You could obviously run the factory better and make deliveries on time if you were given accurate forecasts. But you realize that forecasts will never be accurate, particularly in the datacommunications market where technology is causing products and prices to change rapidly. Alternatively, one could argue that the factory's long delivery intervals are due to inflexible suppliers who can't expedite parts and materials if the factory suddenly needs more. But, on reflection, even this argument is not entirely convincing. Suppose for example that a large shipment of parts and materials arrives unexpectedly, enough to make 50 extra workstations. What would you do with workstations, where would you send them? Let's say there are 100 customers scheduled to receive a workstation this month. On average they've waited say eight months for delivery, but now their machines are in the shipping dock, ready to be loaded onto a delivery truck. Suddenly, 50 more workstations become available. Curiously,

despite the eight month delivery interval, the factory cannot ship the 50 extra workstations, because the order book doesn't show another 50 customers who are *expecting* to receive a workstation this month. Instead it shows 100 customers who are expecting delivery this month, and several hundred customers who are expecting delivery during the next twelve months. It's not a simple matter to ship the extra workstations early -- customers must be informed of early deliveries, so must the sales and field support organization. Moreover, the factory has to adjust the production schedule to account for early deliveries.

As you think about it, the factory's problem is not with late deliveries (since most customers receive their workstations on the promised date) but, instead, with slow deliveries -- workstations are shipped on time, but the agreed delivery interval is too long!! You seem to be gridlocked. How does the factory get out of this delivery situation, and, perhaps more important, how does it avoid extended delivery intervals in the first place?

To help explore these questions a simulation model has been developed of a factory, customers and account executives. The model allows you to think about the different 'players' whose actions and choices regulate orders and production. There are business planners (who provide forecasts), factory schedulers, expediters, customers and account executives. You step into their shoes. You examine their responsibilities, their goals and incentives

and the sources of information that attract their attention -- all with the intention of understanding the logic behind their choices and actions. Then you stand back from the detail and, with the help of diagrams and simulations, you explore how the players interact and cooperate, and how the factory balances supply and demand.

Production Planning and Factory Scheduling

Consider first production planning, which is a multilayer process that consolidates information from forecasters, from product managers and from the factory. Figure 1 shows the information entering the production planning policy.

An important input is the market forecast based on the marketing staff's business plan. The business plan starts from an estimate of total industry volume for all classes of datacommunications equipment. From historical data and various business assumptions (new product introductions, price changes, competitor actions, expected delivery intervals), forecasters compute the company's expected share of industry sales. Then, they multiply industry volume and expected share to generate the company's sales forecast by product line over a two-year planning horizon. The forecasting process is a logical exercise in gathering and processing market information. But as the forecast enters the factory, to be used in production scheduling, it is modified by its own credibility (its reputation for accuracy in the factory), by pressures from inventory, delivery interval

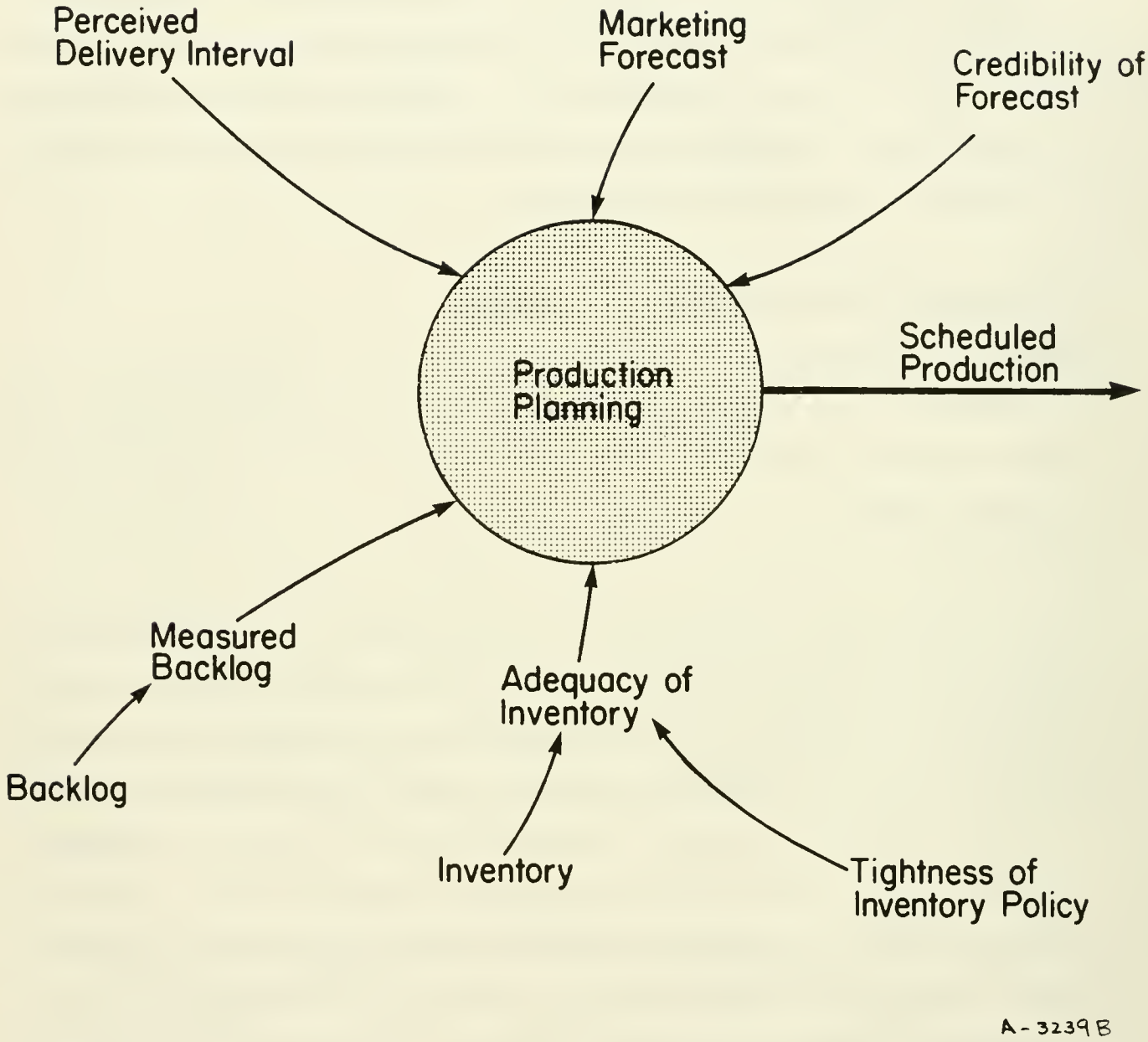

Figure 1: Production Planning

and backlog. Let's consider each of these factors in turn in order to identify the people most responsible for modifying the forecast and their rationale for doing so.

Let's begin with the forecast credibility. It is quite common in datacommunications companies for market forecasts to lack credibility at the factories. The reasons are easy to understand. The datacommunications market is in flux. New products are introduced almost daily, prices change frequently, new competitors spring up. Factory managers feel that forecasters simply don't know the sales potential of a given product line (despite their elaborate forecasting methods) and therefore, forecasts are often pared-down, to be 'on the safe side', and particularly to avoid the very visible inventory costs resulting from excess production.

What if the forecast is inaccurate? How does the factory know of the error, what source of information would reveal the error, who would be responsible for adjusting the production schedule and would they have the incentives and appropriate information to make the correct adjustment? Now we are getting into the heart of factory scheduling, stepping into the shoes of the schedulers themselves.

The production schedule is defined over a rolling six-month horizon. One can envisage a planning chart, with boxes marked across a page. The extreme left-hand box shows the number of units of a given product-line

(say workstations) scheduled for production in the current month (in fact the schedule may be expressed in weeks or even days, but it makes no difference for this discussion). The extreme right-hand box shows the number of units scheduled for production six months from now. The boxes in-between show monthly scheduled production for months 2 through 5. Each month the planning chart is updated, the current month's box 'drops off' the left-hand side of the chart, and a new box 'rolls in' on the right-hand side, rather like the steps on a moving escalator. The number in the new box is the forecast of customer orders six months hence.

The scheduler assigns incoming customer orders to the appropriate box. To understand the process, imagine that the factory is trying to deliver on a three month interval. A new customer order is received (say an order for a workstation) which is due for installation and shipment in three months time. The scheduler looks in the planning chart for the box corresponding to month 3. He finds a workstation that is scheduled for production and assigns the customer order to it. That particular workstation is now 'earmarked' for a customer and cannot be assigned again.

The process works smoothly as long as the original forecast was accurate. But what happens when the forecast is low? Again the factory is trying to deliver on a three month interval. Based on the forecast, 100 workstations have been scheduled in the time slot three months hence. But orders for 150 workstations arrive. The scheduler assigns the first 100 orders

exactly as before, until the entire box is assigned. Then he assigns the remaining 'unexpected' orders to the next available box -- in other words to a later time slot. Having done so, he then informs the salesforce that workstations are available only on an extended delivery interval. Because of the long production planning horizon, schedulers can almost always find an open production slot for a new customer order. When a customer order has been assigned a production slot, the scheduler has done his job. So schedulers, who are 'close' to the customer order backlog, and therefore the first people in the company to see when the forecast is too low, have no incentive to argue for higher production, as long as production slots remain open.

The same logic works in reverse. When the forecast is optimistic and production is scheduled in excess of customer orders, schedulers begin to find early time slots for new customer orders. So a scheduler might receive an order for a workstation due in three months, but finds he can assign it to an open production slot only two months hence. The scheduler has done his job, so again, although he knows the factory is producing the wrong amount (too much) he has no incentive to argue for a lower production plan. However, in this case, pressure to reduce the production plan will eventually come from finished inventory. If customers are unable to take an early delivery , then products awaiting shipment will accumulate in finished inventory and signal a factory manager to curtail production.

Customer Ordering

Figure 2 shows the influences on customer ordering. Sales effort is the principal influence, because customers must learn about the company's products before they will even consider purchase. Then, once the customer is aware of the product, traditional factors such as price/performance and delivery interval become important.

Let's suppose for the sake of simplicity that the price/performance of a given product line is constant, and that sales effort (which you can think of as the number of hours per month the salesforce spends with customers) is constant. How do customer orders vary with changes in delivery interval? Think about this question from the perspective of account executives as they contact potential customers. Suppose that account executives have been selling workstations on a three month delivery interval. Then factory schedulers announce that the interval must be extended to five months. Account executives can still sell workstations on the five month interval, but they will take longer to find a customer who is willing to wait the extra two months. The net effect is that customer orders decline as the interval rises, and conversely, that customer orders increase as the interval falls.

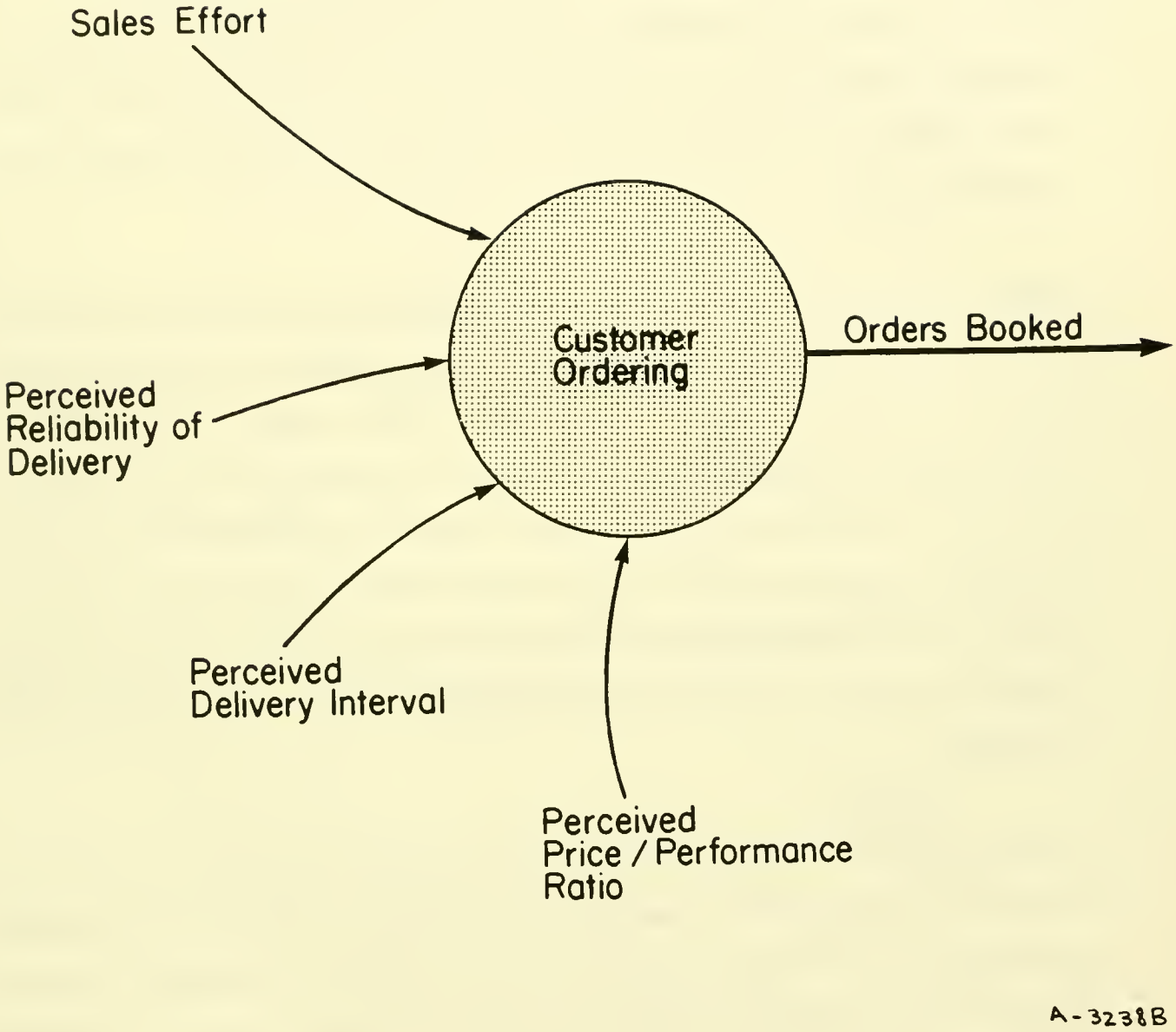

Figure 2: Customer Ordering

DYNAMICS OF PRODUCTION SCHEDULING AND CUSTOMER ORDERING

If one accepts that customers, planners and schedulers behave as described above, then how do they interact? To answer this question let's first visualize the feedback loops connecting the 'players'. There are two important loops.

Figure 3 shows a negative feedback loop connecting customers' ordering to the company's deliveries. Consider the loop's operation if product suddenly becomes less available (the factory shuts down, or there is a transportation strike). Shipments decline, causing delivery interval to rise. When the delivery interval rises it takes more time for salespeople to make a sale, so that, for any given sales effort, customer orders decline and the total number of orders booked stabilizes. Here is a self-regulating demand mechanism that brings customer orders into an exact balance with shipments.

Figure 4 shows a positive feedback loop connecting cutomers' ordering to forecasting, production scheduling and shipping. This loop can readily generate self-fulfilling forecasts, as the following argument shows. Suppose that production declines due to a previously inaccurate forecast. A decline in production quickly curtails shipments (assuming that the factory keeps very little finished inventory). When shipments fall, the delivery interval rises, time per sale increases and customer orders fall. When orders fall, market share declines, and so eventually does expected

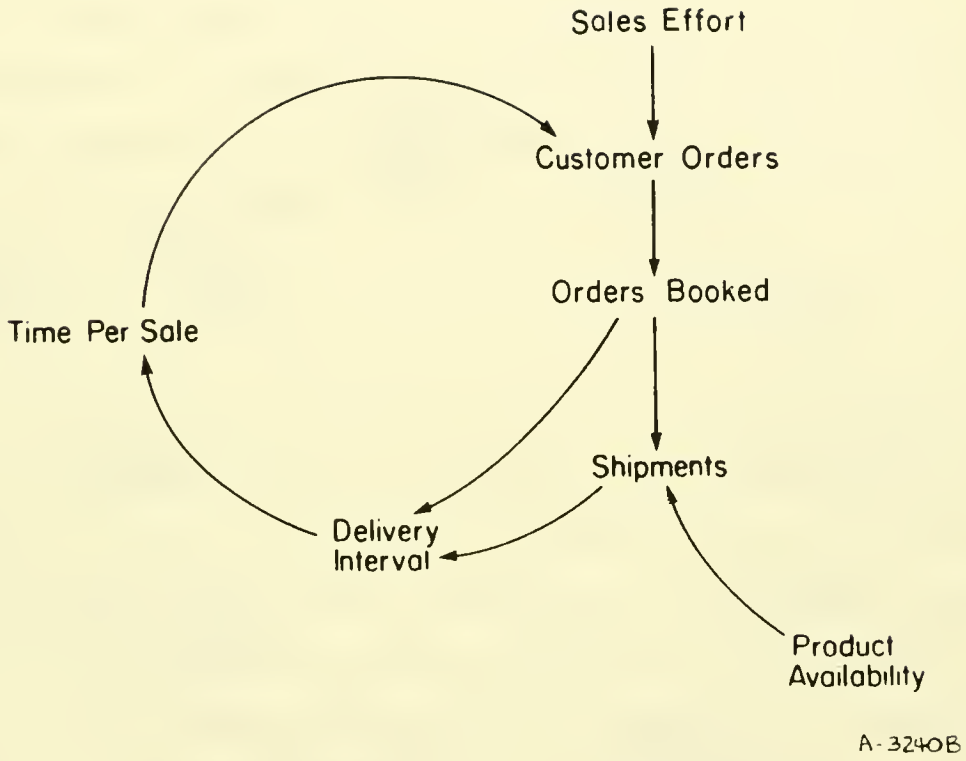

Figure 3: Negative Feedback Loop Connecting Customers' Ordering to Shipments and Delivery Interval

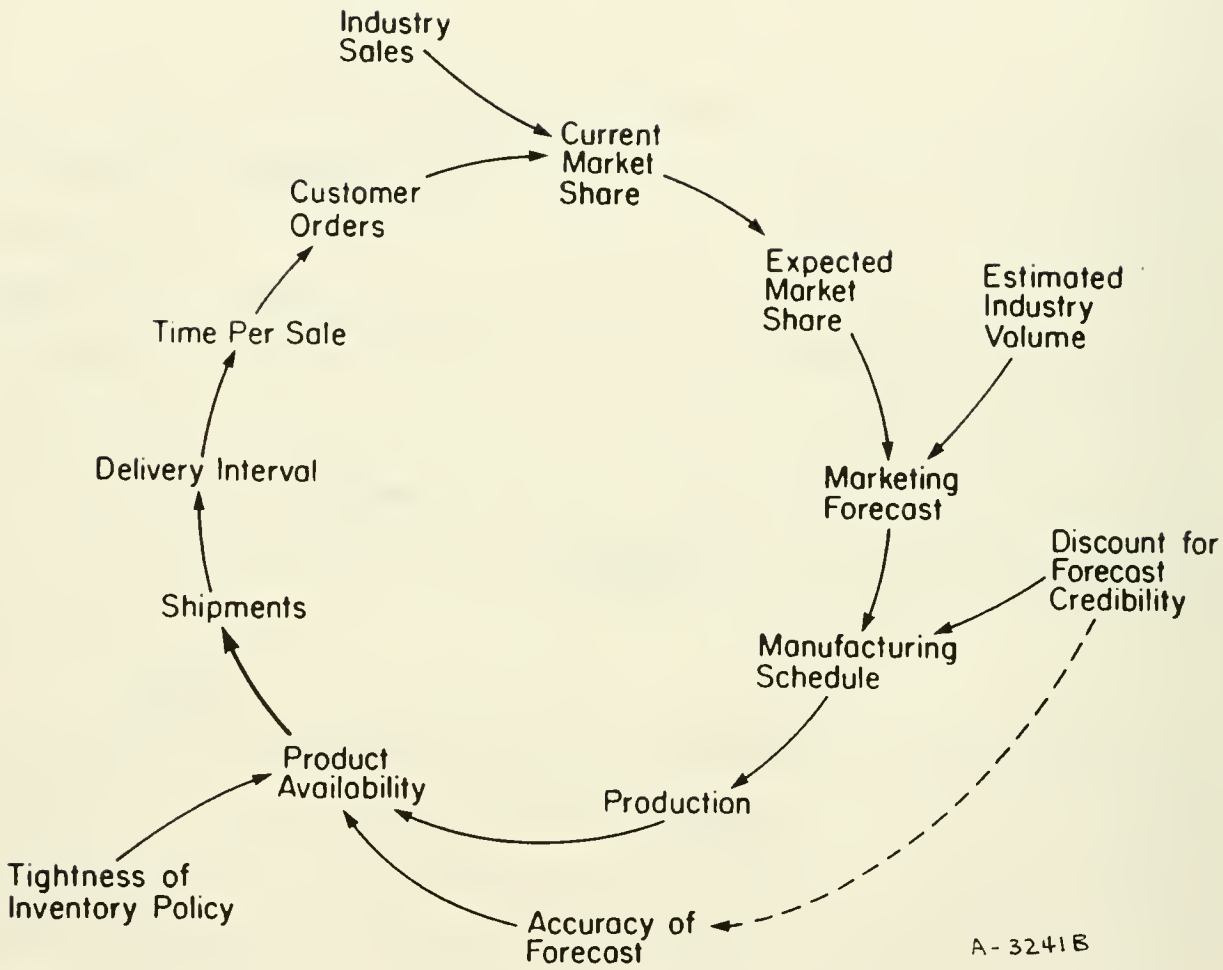

Figure 4: Positive Feedback Loop Connecting Customers' Ordering to Forecasting, Scheduling and Shipping

market share, as it is based largely on historical data. Because expected share falls, the marketing forecast is further reduced and so too is the production schedule and the production rate. The initial product shortage therefore feeds back to reinforce itself.

In the real system the two loops are combined. We can use simulation to understand how they operate. Figure 5 shows the system's response to a one time twenty percent increase in sales effort (the reader should note that, in the factory model, sales effort is 'exogenous' -- the modeler is free to set sales effort at any value he thinks appropriate. In this case, we know, from the sales planning and control model described in D-3806, that sales effort in a datacommunications company can vary widely depending on the terms of the compensation scheme. So a simulation experiment that assumes a large, twenty percent, increase in sales effort is certainly plausible). The model starts in equilibrium, with customer orders (-1-) and production (-2-) of 100 units per month. When sales effort increases, orders (-1-) increase correspondingly to a peak of 120 units per month. However, as time goes by, orders (-1-) are gradually eroded until they settle at a new equilibrium of 110 units per month -- an increase of 10 units a month, but only half the possible increase. Meanwhile production (-2-) increases slowly and steadily until it exactly equals customer orders (-1-). But why are orders permanently depressed? As figure 6 shows, the immediate cause is delivery interval (-1-) which rises from 3 months to a permanently higher value of 3.75 months. Fewer customers are

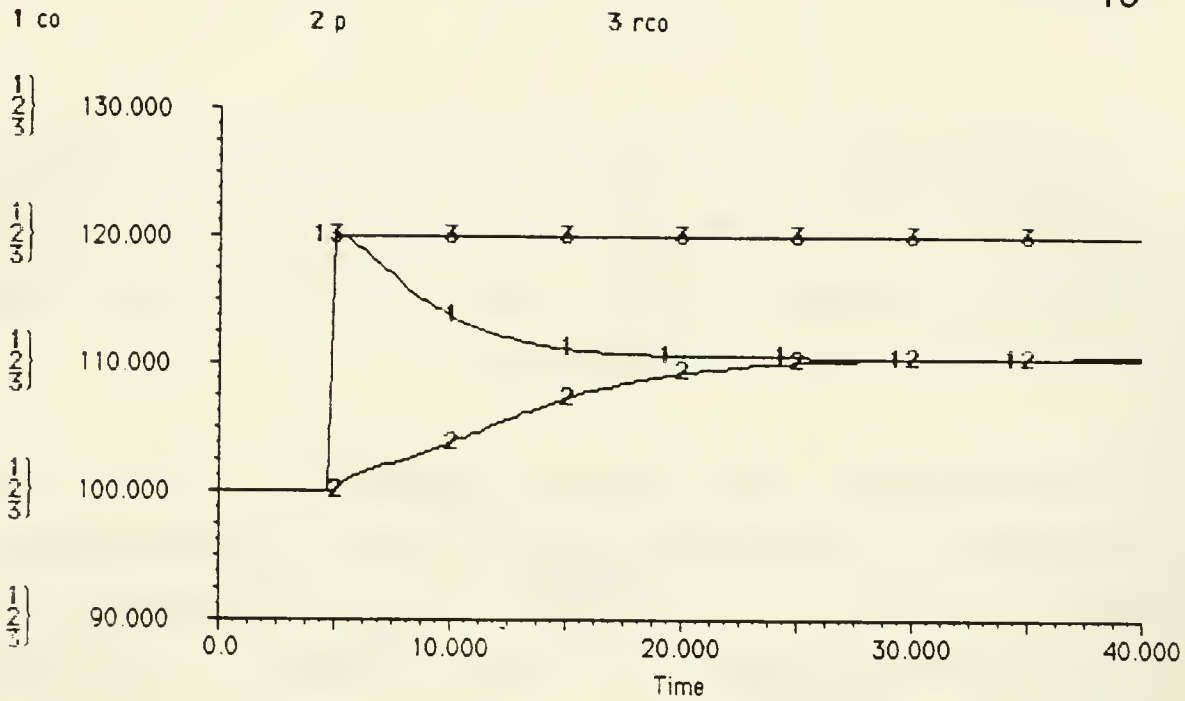

Figure 5: Customer Orders and Production - 20% Step in Sales Effort

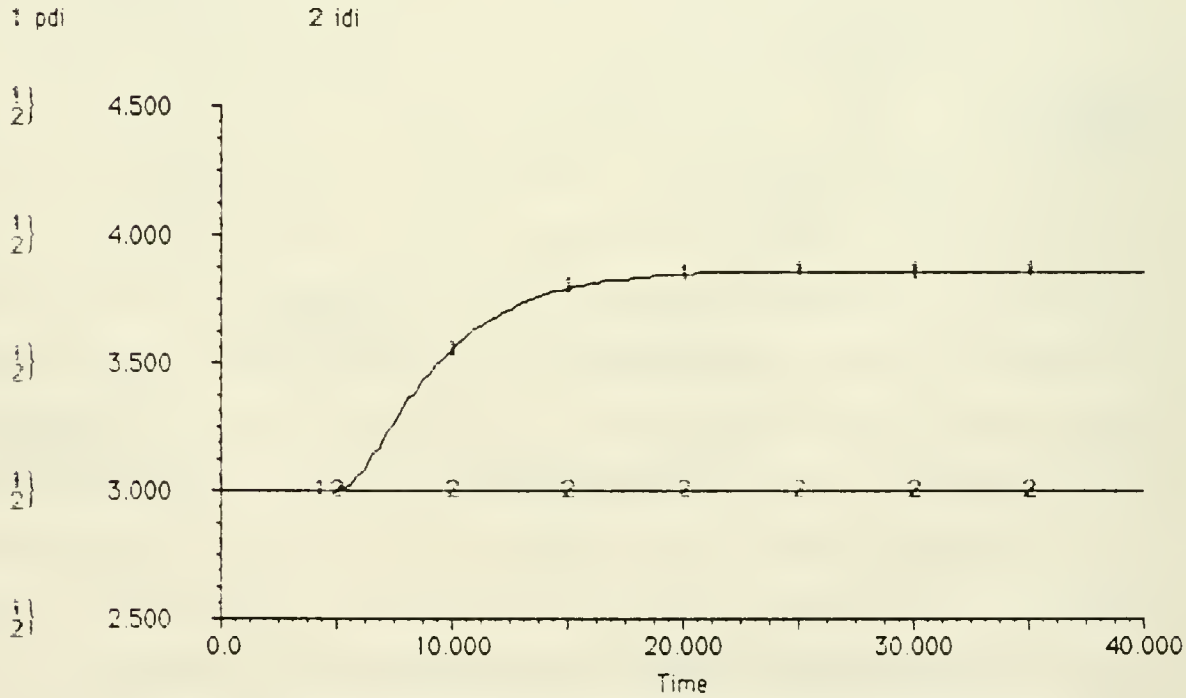

Figure 6: Delivery Interval -- 20% Step in Sales Effort

willing to place an order when the interval is extended.

But why doesn't the interval fall back to three months once the surge of orders has passed? To answer this question we need to look closely into the 'mechanics' of forecasting and scheduling. Figure 7 provides part of the story. When orders increase unexpectedly, the forecast increases too, but only gradually. As customer orders (-2-) decline (due to increased delivery interval), the forecast (-1-) changes course. Instead of continuing upward toward reference customer orders (-3-), (the value that customer orders would achieve if delivery interval were fixed at three months) it homes in slowly on the final and depressed value of orders. In other words, the forecast is self-fulfilling. The only way out of this trap is to schedule production in excess of the forecast. But there is no pressure on the factory schedulers to do so. Figure 8 shows why. When customer orders are unexpectedly high, the schedulers simply assign the excess orders to the earliest convenient slot in the pre-planned manufacturing schedule. So the surge of orders is absorbed by consuming a larger proportion of the pre-planned schedule (-1-) instead of expanding the schedule by adding the excess orders to the forecast. As a result, orders booked (-2-) rise too high -- higher than they should if deliveries are to remain competitive -- yet, at the same time, the illusion exists in the factory that the customers are satisfied, since each customer order is assigned a production slot and scheduled for delivery on a date that the customer has

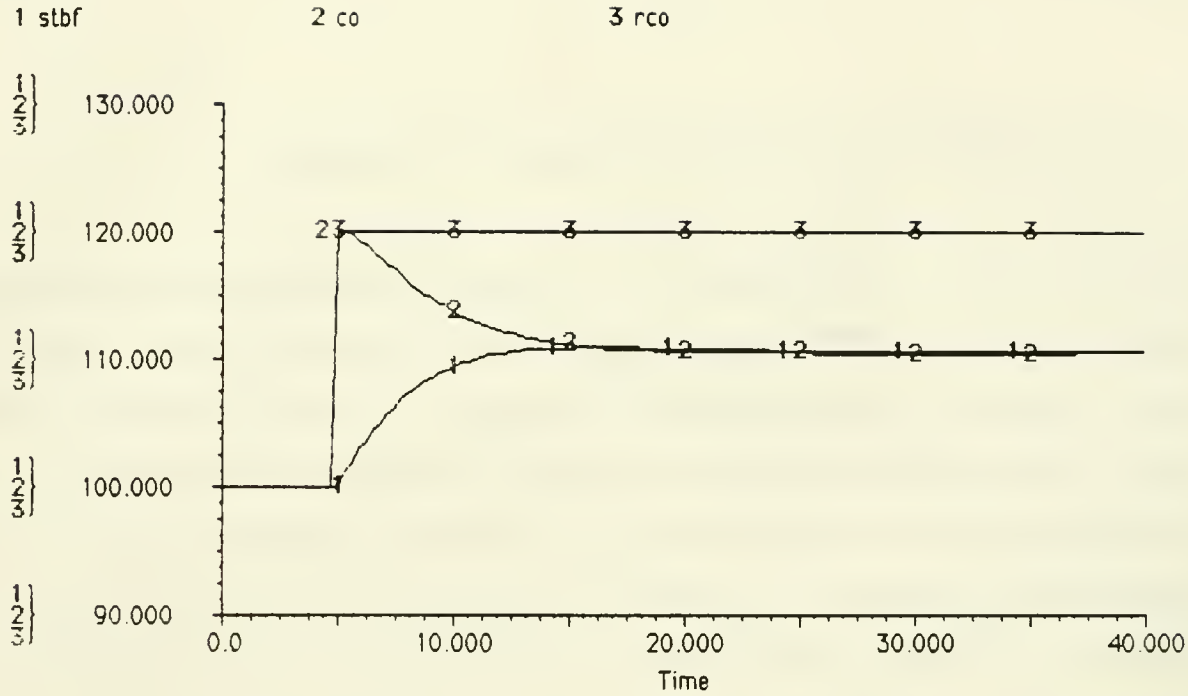

Figure 7: Self-Fulfilling Forecast -- 20% Step in Sales Effort

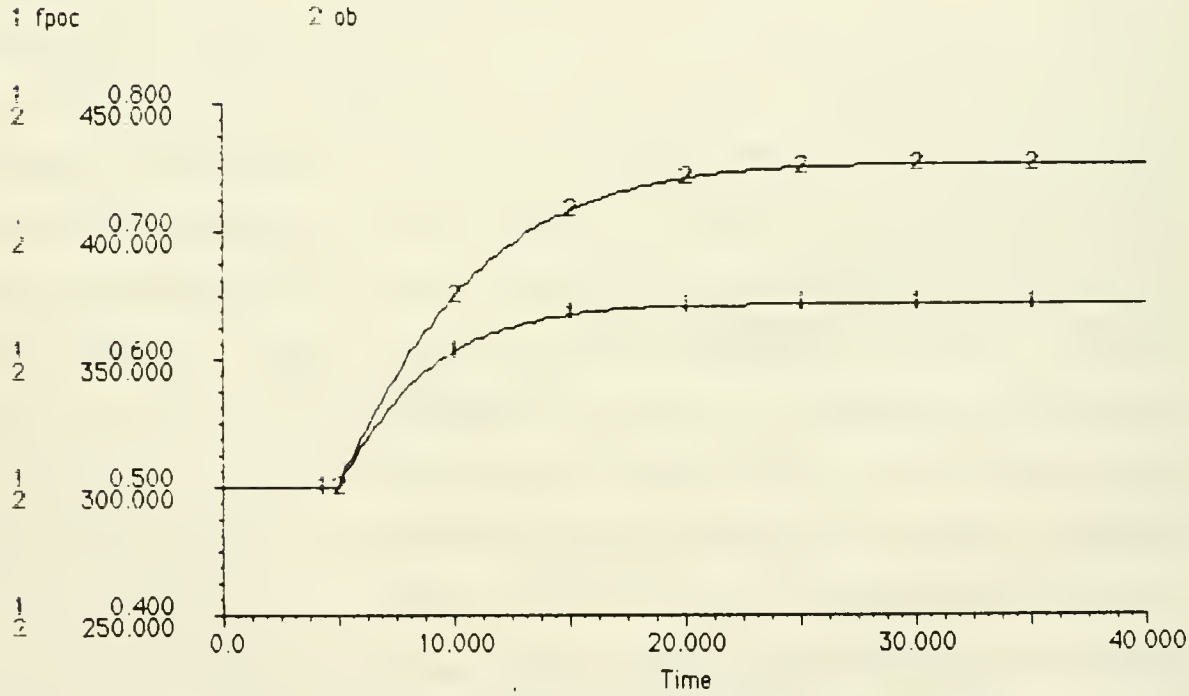

Figure 8: Fraction of Planned Orders Committed and Orders Booked -- 20% Step in Sales Effort

agreed to. The illusion is easily sustained, because the factory keeps the salesforce up-to-date on the earliest time slots available in the production schedule, so salespeople tend to find customers who are satisfied with the factory's schedule.

SELF-SUPPRESSING DEMAND

The simulations above show that the factory's forecasting and scheduling policies fail to regulate delivery interval -- instead they allow the interval to drift upward whenever the forecast is too low. As a result, the factory can inadvertently suppress orders for its growing product lines. To understand how, consider the case of a new product line which is attracting a growing proportion of sales effort. Think back to simulations of the sales planning and control model in D-3806. Customer orders can grow very quickly. They can double in six months, not because customers are stampeding to buy, but instead because the salesforce is anxious to sell! With such rapid salesforce-induced growth it's easy for the sales forecast to be too low, not just for a week or a month, but for six months or a whole year. With a low forecast, the factory's scheduling policies allow delivery interval to drift upward. The interval will continue to drift upward until it is high enough to deter customers from buying and salespeople from allocating still more time to selling the product. Customer orders will therefore stop growing. So the interaction of factory scheduling and salesforce time allocation will suppress demand for the new product line.

POLICIES TO CONTROL DELIVERY INTERVAL

To prevent the problem of self-suppressing demand the factory needs to manage the delivery intervals of its different product lines, to ensure the intervals remain competitive. The idea of managing intervals here means more than implementing a special interval reduction program. Such programs typically occur only when intervals are so high that they attract senior management attention. By then the image of extended intervals is already well-established with customers and with the salesforce, and many potential orders have been lost. Managing intervals means establishing a routine policy, at the level of schedulers and planners, that rapidly detects systematic bias in the forecast and compensates for it by scheduling production in excess of the forecast. Two possible interval control policies are described and simulated below.

Monitoring and Control of Excess Orders

The first policy requires schedulers to monitor *excess* orders and use them to adjust the forecast. An example is helpful to explain. Suppose the factory is planning production of workstations over a six-month horizon and is now delivering workstations with an interval of three months (competitive for the industry). In the current month the factory receives 120 orders for workstations, due for delivery three months hence. The scheduler looks at planned orders three months into the planning horizon. He finds only 100 workstations scheduled for that month -- 100 being the forecast of orders generated three months ago, at the start of the planning

process. With the present procedure the scheduler puts the 20 excess orders into next month's time slot and then informs the salesforce of the schedule change. With the proposed system the scheduler would, in addition, count-up all excess orders (all orders whose scheduled delivery date is greater than three months -- 20 in this case) and communicate the number to production planners. Each month the planners would add the excess orders to the current month's forecast. (This procedure may seem to result in double scheduling because the schedulers first assign the 20 excess customer orders and then the planners add 20 units of production to the forecast. But in fact a customer order is scheduled once, and once only, by the scheduler. The planners use the 20 excess orders as a guide for increasing the forecast. Their concern is with planning the volume of future production, not with scheduling individual customer orders).

The same procedure could also be used to reduce the production plan to compensate for a high forecast. In this case the scheduler would count-up all planned orders in the time slots before month three that have not been assigned a customer order. He would then communicate this number of excess planned orders to production planners. The planners would subtract the excess orders from the current month's forecast.

Figure 9 shows a simulation of the order monitoring and control policy, with a 20 percent increase in sales effort. The reader should compare figure 9 with figure 5. As before, when sales effort increases, customer orders (-1-) increase correspondingly to a peak of 120 units per month. After the peak however, orders (-1-) decline only slightly, and then settle at an equilibrium of 120 units per month. Meanwhile, production (-2-) increases slowly until it exactly equals customer orders.

Figure 10 shows, that with the new policy in operation, delivery interval (-1-) stays close to three months, despite the surge of orders. So the factory no longer suppresses demand due to extended intervals. The improvement in delivery performance occurs because planners expand the production schedule more quickly than the forecast alone would suggest.

Figure 11 shows what is happening. From month 0 to month 5, the forecast (-1-) is steady at 100 units per month. In month 5 (the time when customer orders increase) the forecast (-1-) starts to rise, but only gradually because forecasters do not anticipate (by assumption) the step increase in sales effort that is causing the extra demand. By month 10, the forecast (-1-) has risen to 110 units per month (in other words, in month 10, forecasters are saying that, six months hence -- in month 16, orders will be 110 units per month). But production planners are planning to produce 130 units per month in month 16 (-2-) -- much more than the forecast and more even than the initial peak of customer orders!! Their

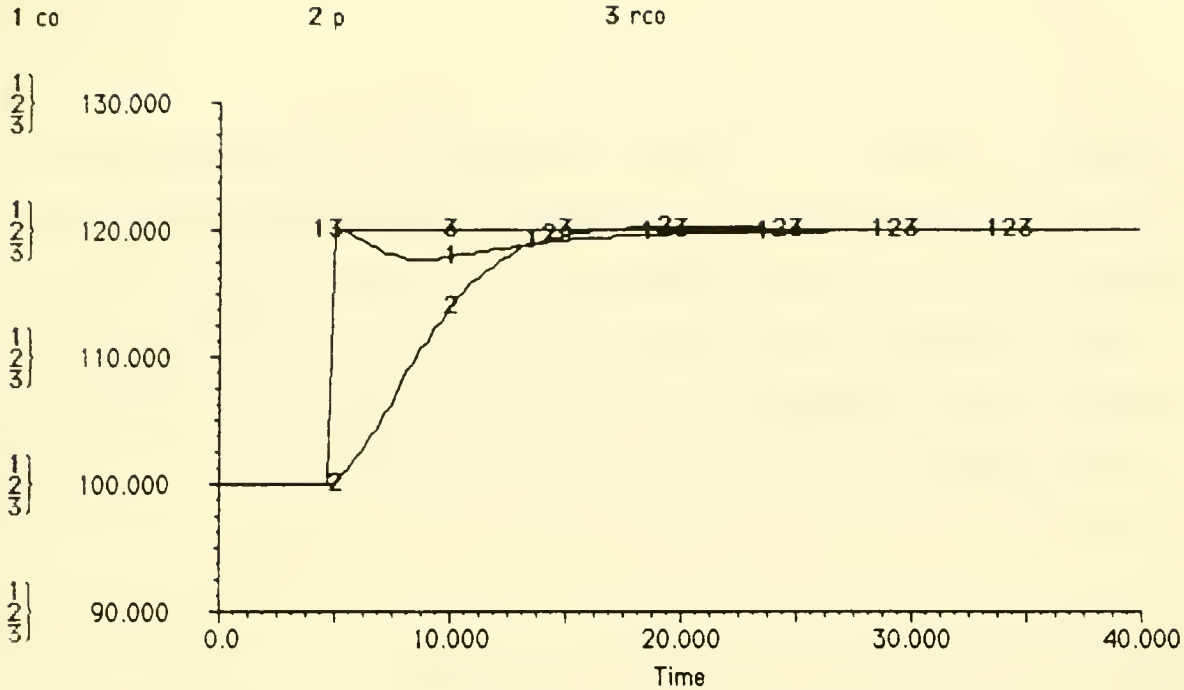

Figure 9: Customer Orders and Production with Order Monitoring and Control

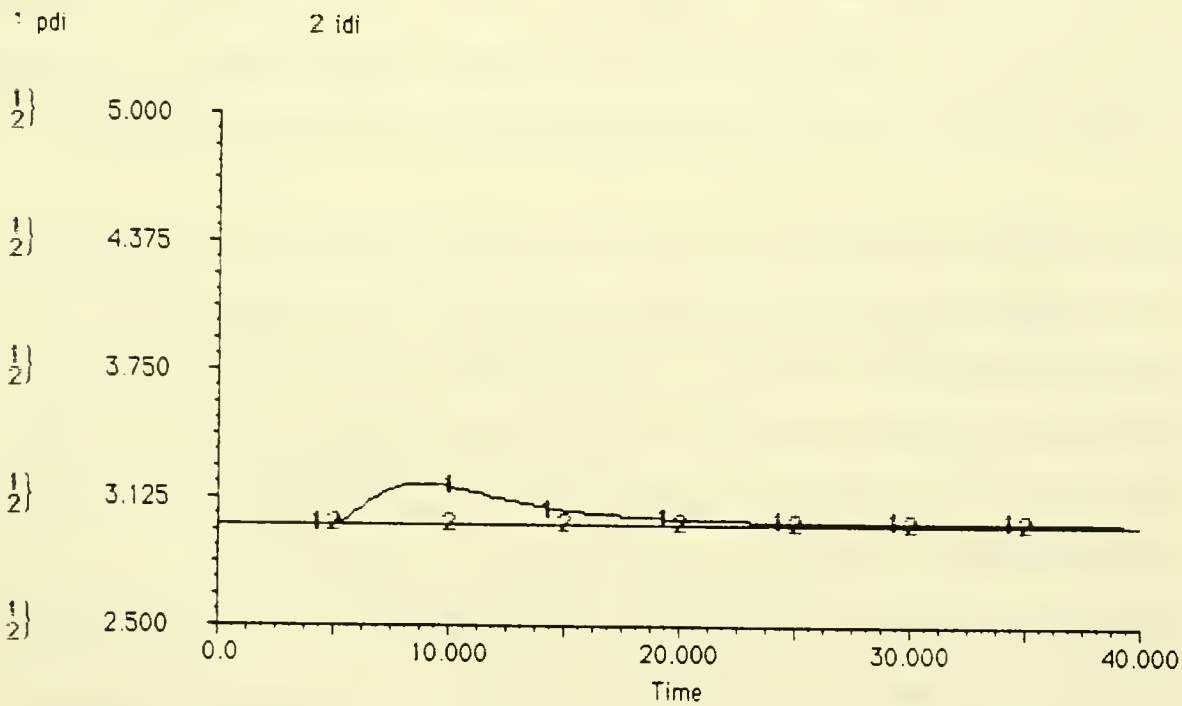

Figure 10: Delivery Interval with Order Monitoring and Control

plans (-2-) continue to exceed the forecast up to and beyond month 20, though the discrepancy gradually diminishes. But how can the planners be confident they are making the correct decisions? Figure 12 provides the answer. Schedulers are tracking excess orders (-4-) and reporting them weekly to the planners. In month 10 the schedulers report more than 20 excess orders (-4-). So the planners increase the monthly production schedule (-2- in figure 11) by 20 units above the forecast.

More Finished Inventory and Inventory Control

The factory can also regulate delivery interval by holding a comprehensive finished inventory (or nearly-finished inventory) and sending information on the inventory level to production planners. The inventory is to be used as a buffer, to allow the factory to ship promptly regardless of whether weekly customer orders correspond exactly to weekly production.

You might think that the idea of a buffer inventory comes straight from the textbook. But in fact it does not. The crucial difference is that the proposed buffer inventory is used as a *source of information* to tell production planners when customer orders deviate systematically from the forecast. Traditional buffers are not used to detect systematic error in the forecast, because planners assume that the difference between customer orders and forecast is random -- so a glut of orders this month (relative to forecast) will be balanced by a corresponding shortfall next month. If planners believe their forecasts contain only random (not

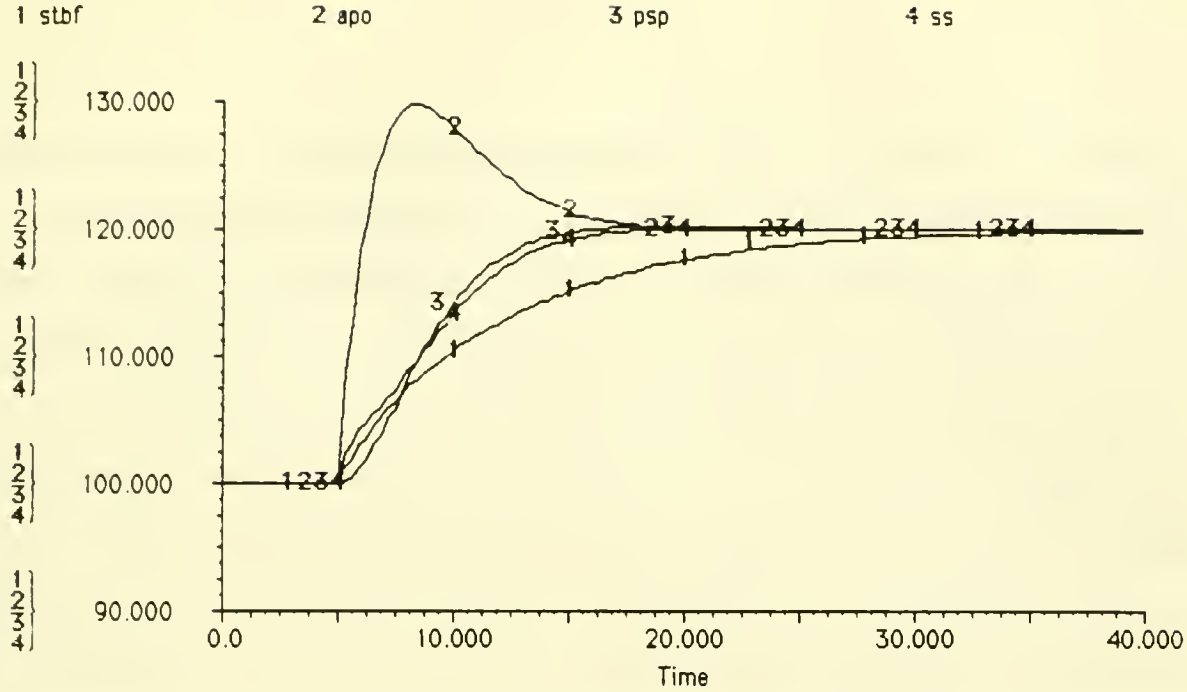

Figure 11: Forecast and Additions to Planned Orders with Order Monitoring and Control

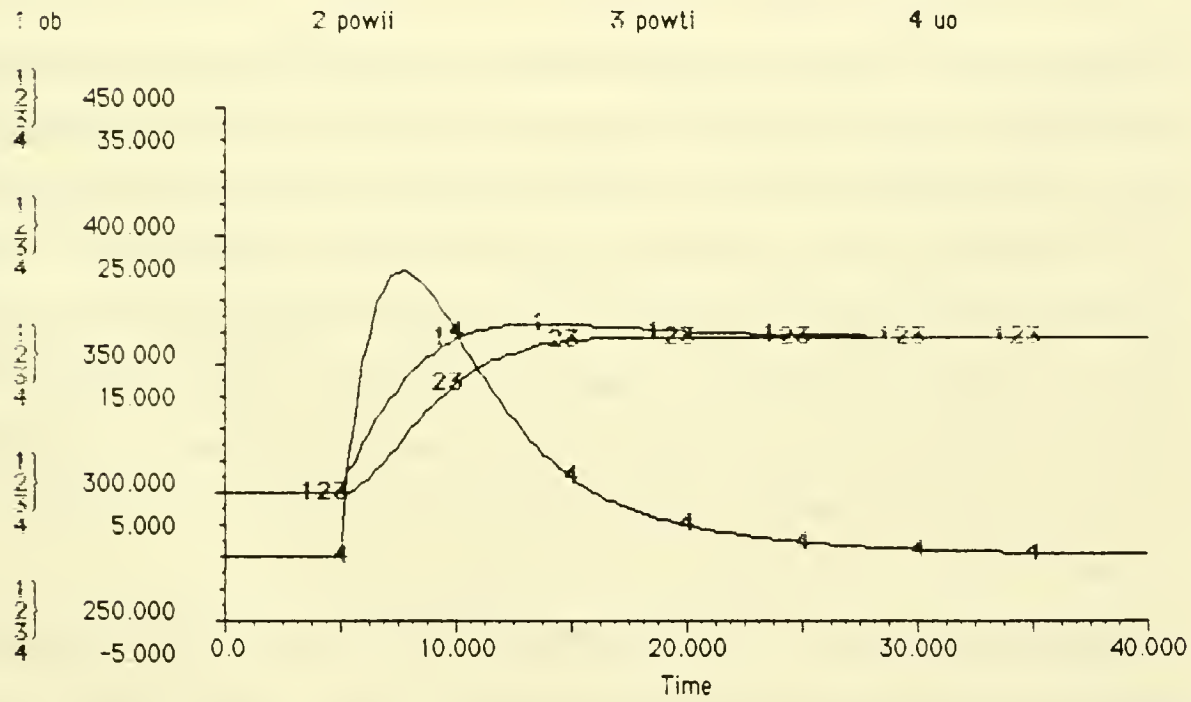

Figure 12: Excess Orders with Order Monitoring and Control

systematic) error, then they install a buffer inventory to cover the most extreme glut of orders and use the forecast alone for production planning. But in the fast-moving datacommunications market it's quite easy for forecasts to be systematically low or high for months or even years at a time. In this situation, movements in the buffer inventory are crucial indicators of whether the factory's forecasts are optimistic or pessimistic. The inventory level is monitored frequently (say weekly), compared with a standard (perhaps three months worth of the average mix of shipments) and the discrepancy reported to production planners. The planners should add a fixed proportion of the discrepancy (say one half) to the base 6-month market forecast.

Holding three months of finished inventory might seem like an expensive proposition. But one should remember what the investment is intended to buy -- timely information on whether demand (potential customer orders) is exceeding supply (planned production), whether demand is in exact balance with supply, or whether it is lower than supply. For a product-line that is growing faster than expected, information from changes in the buffer inventory can prevent the company from suppressing its own orders. In this case the inventory's value to the company (per year) is equal to the product line's profit margin multiplied by potential annual growth in volume of sales. A numerical example will illustrate. Let's suppose the product line's profit margin is $1000 (on a $5000 unit), that the industry growth rate for similar products is 50 percent per year, and that current

sales volume is 1000 units per year. If the company had invested in finished inventory to stabilize its delivery interval, its orders would keep pace with the industry trend, and reach 1500 by year-end. Without the inventory, the factory inadvertently suppresses demand, so customer orders remain static at 1000 units per year. The presence of the inventory creates 500 extra orders, each worth $1000 in profits, for a total benefit of $0.5 million over the year. The carrying cost of the inventory (assuming 3 months (0.25 years) coverage and a 10 percent interest rate) is only $0.125 million -- a quarter of the benefit! Of course one would want to look more closely at the benefits and costs in a real situation -- but the simple calculation above gives the flavor. If self-suppressing demand is a real possibility for a product-line with high growth potential and high margin (high growth and margin tend to go together) then it is quite easy for a return on finished inventory investment to be 100, 200 or even 300 percent per year. (As a matter of interest, there is a general formula for calculating return on inventory investment in situations where self-suppressing demand is possible. If g is the industry growth potential, ppm is the percent profit margin on the product-line, c is the inventory coverage -- expressed as a fraction of a year, and i the interest rate, then the return on inventory investment is (((g*ppm)/(c*i))-1)*100).

Figure 13 shows a simulation of the finished inventory monitoring and control policy, with a 20 percent increase in sales effort. The reader should compare figure 13 with figure 5. As before, when sales effort

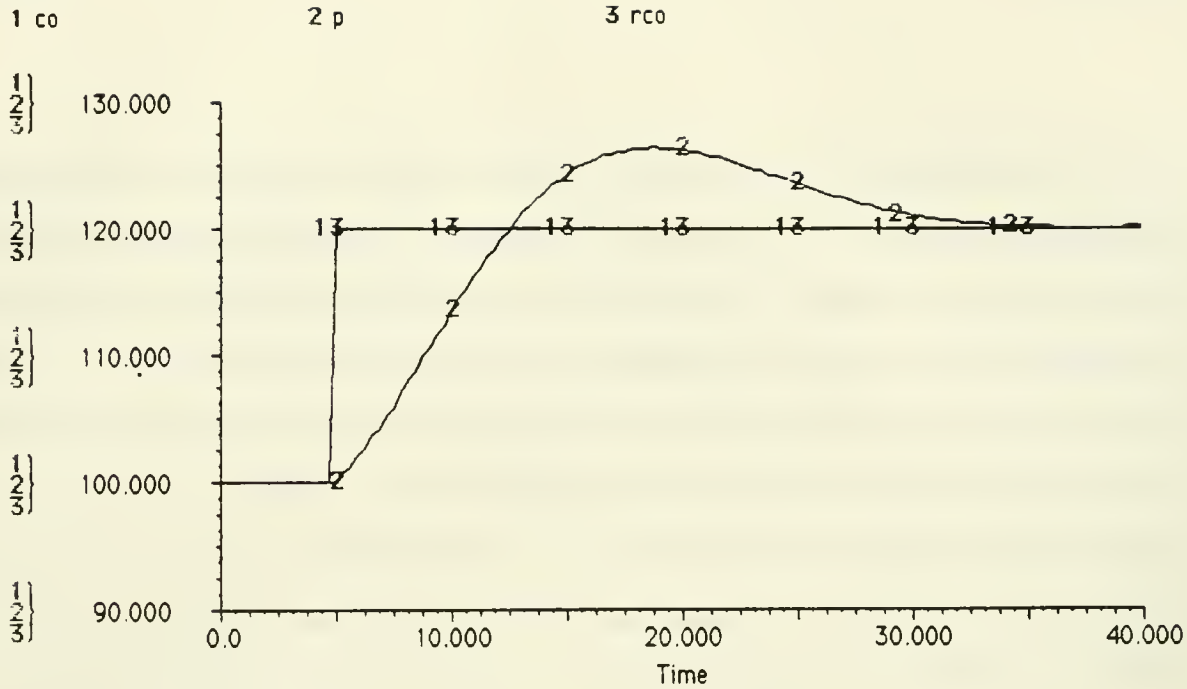

Figure 13: Customer Orders and Production with Finished Inventory Control

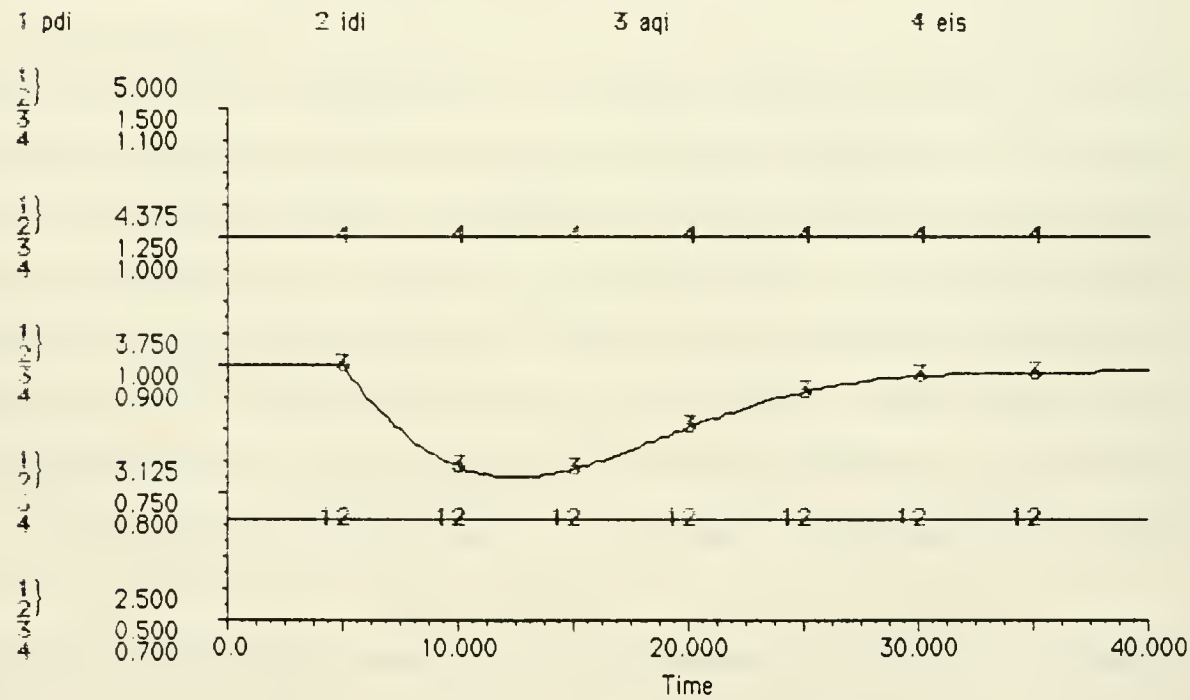

Figure 14: Delivery Interval with Finished Inventory Control

increases, customer orders (-1-) increase correspondingly to 120 units per month. Now however, orders (-1-) remain constant rather than declining. Meanwhile, production (-2-) increases slowly until it equals customer orders in month 12. Production (-2-) continues to grow, peaks at about 125 units per month then gradually declines until it balances exactly with orders. The production overshoot enables the factory to re-build its depleted finished inventory back to 3 months worth of shipments.

Figure 14 shows that the new policy holds delivery interval (-1-) rock steady at 3 months -- because there is adequate inventory on hand to prepare and ship all customer order in three months, despite the unexpected surge of orders. In other words the finished inventory acts as a buffer to insulate shipments from production. Figure 15 shows how inventory also acts as a source of planning information for production planners. In month 5 (when customer orders step-up) inventory (-1-) declines, because shipments exceed production. At the same time authorized inventory (-2-) begins to rise, because shipments are now higher and the factory needs more finished inventory in order to maintain 3 months coverage of shipments. The difference between authorized inventory (-2-) and actual inventory (-1-) is the signal that planners use to increase the production plan -- it's the analogy of excess orders in the order control policy. Planners add half the inventory discrepancy to the six-month forecast in order to compute planned production six-months ahead. The simulation shows that the planners' correction to the forecast

(-4-) rises to a peak of 20 units per month by month 12, declines to zero by month 27 and goes slightly negative between months 28 and 40. With the inventory control policy in effect, planners expand the production schedule more quickly than the forecast alone would suggest -- just as they did with the order control policy. Figure 16 shows what is happening. As before, the short-term business forecast (-1-) rises slowly from 100 to 120 units per month. In month 10, forecasters are predicting that customer orders will be 110 units per month in six months time. But in month 10, planners are preparing to produce 125 units per month (-2-) by month 16. They justify the extra planned production on the basis of the finished inventory shortfall. In fact, the shortfall tells them to plan above forecast all the way from month 5 to month 25 of the simulation. The extra planned production replenishes and builds finished inventory.

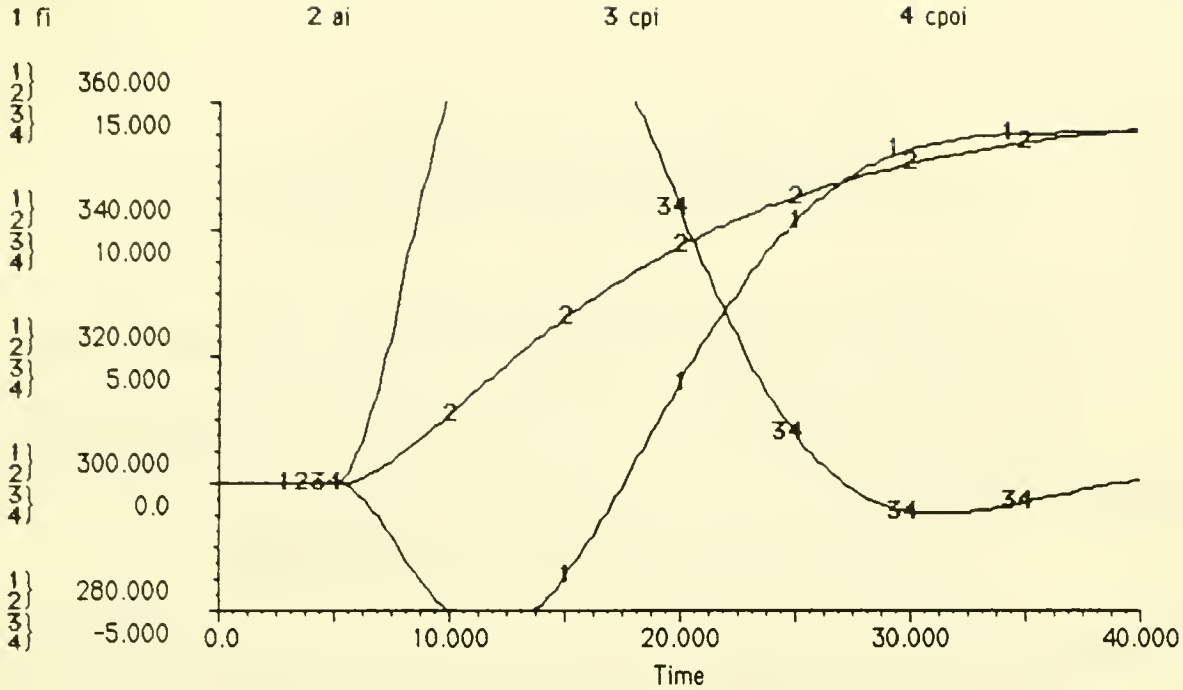

Figure 15: Finished Inventory and Authorized Inventory

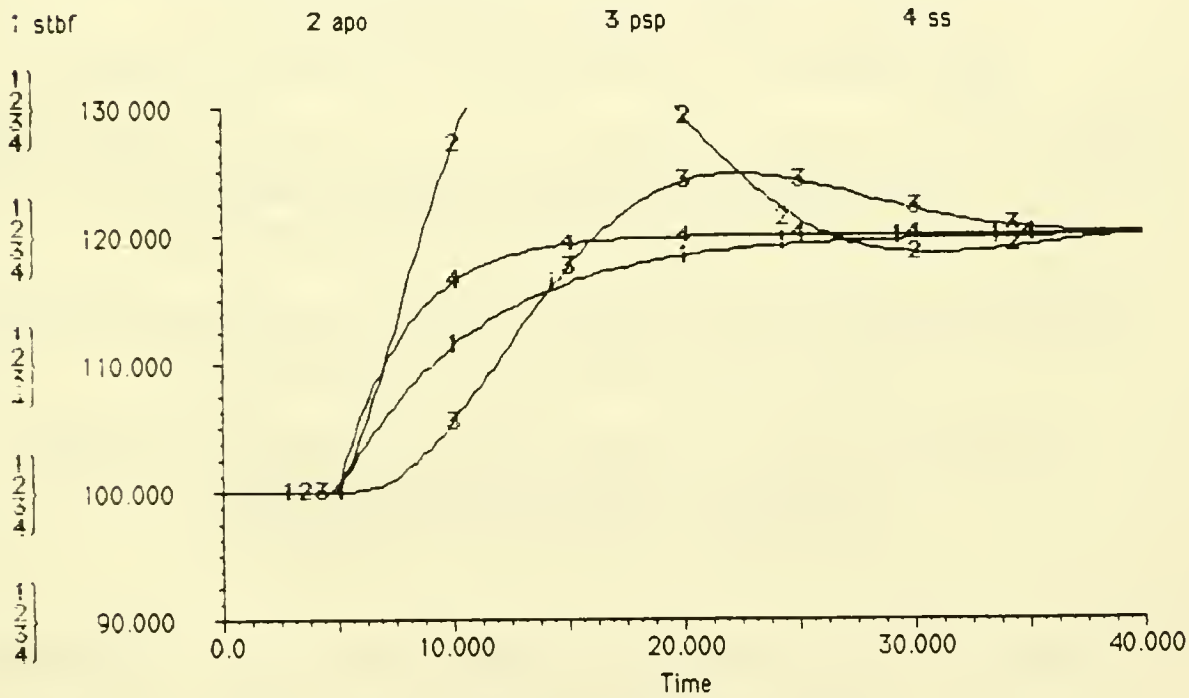

Figure 16: Forecast and Additions to Planned Orders with Finished Inventory Control

DOCUMENTATION OF THE SALES AND PRODUCTION SCHEDULING MODELS

Policy Structure of the Sales and Production Scheduling Model

STELLA Diagram of Customer Ordering and Forecasting in the Base Sales and Production Scheduling Model (saps_base)

STELLA Diagram of Delivery Interval in the Base Sales and Production Scheduling Model (saps_base)

STELLA Diagram of Production Scheduling and Expediting in the Base Sales and Production Scheduling Model (saps_base)

STELLA Equations for the Base Sales and Production Scheduling Model (saps_base)

STELLA Diagram of Order Monitoring, Production Scheduling and Expediting in the Sales and Production Scheduling Model with Order Monitoring and Control (saps_ordmon)

STELLA Equations for the Sales and Production Scheduling Model with Order Monitoring and Control (saps_ordmon)

STELLA Diagram of Customer Ordering and Forecasting in the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

STELLA Diagram of Finished Inventory Control and Shipping in the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

DOCUMENTATION OF THE SALES AND PRODUCTION SCHEDULING MODELS – CONTINUED

STELLA Diagram of Delivery Interval in the
Sales and Production Scheduling Model
with Finished Inventory Control (saps_invcon)

STELLA Diagram of Order Monitoring, Production Scheduling and Expediting
in the Sales and Production Scheduling Model
with Finished Inventory Control (saps_invcon)

STELLA Equations for the Sales and Production Scheduling Model
with Finished Inventory Control (saps_invcon)

Description of New Structure and Equations to Convert
(saps_base) to (saps_ordmon) and to (saps_invcon)

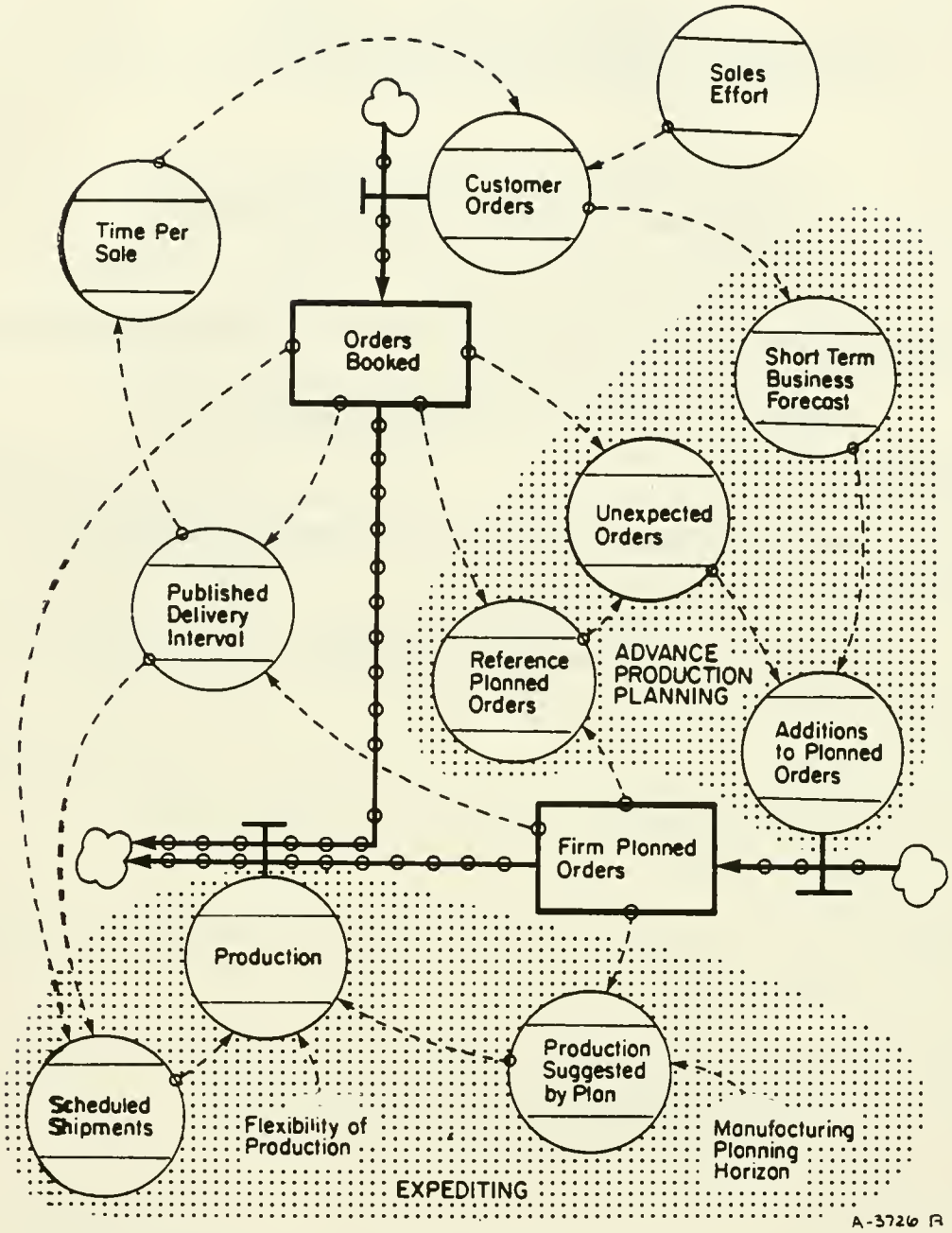

Figure17: Policy Structure of the Sales and Production Scheduling Model

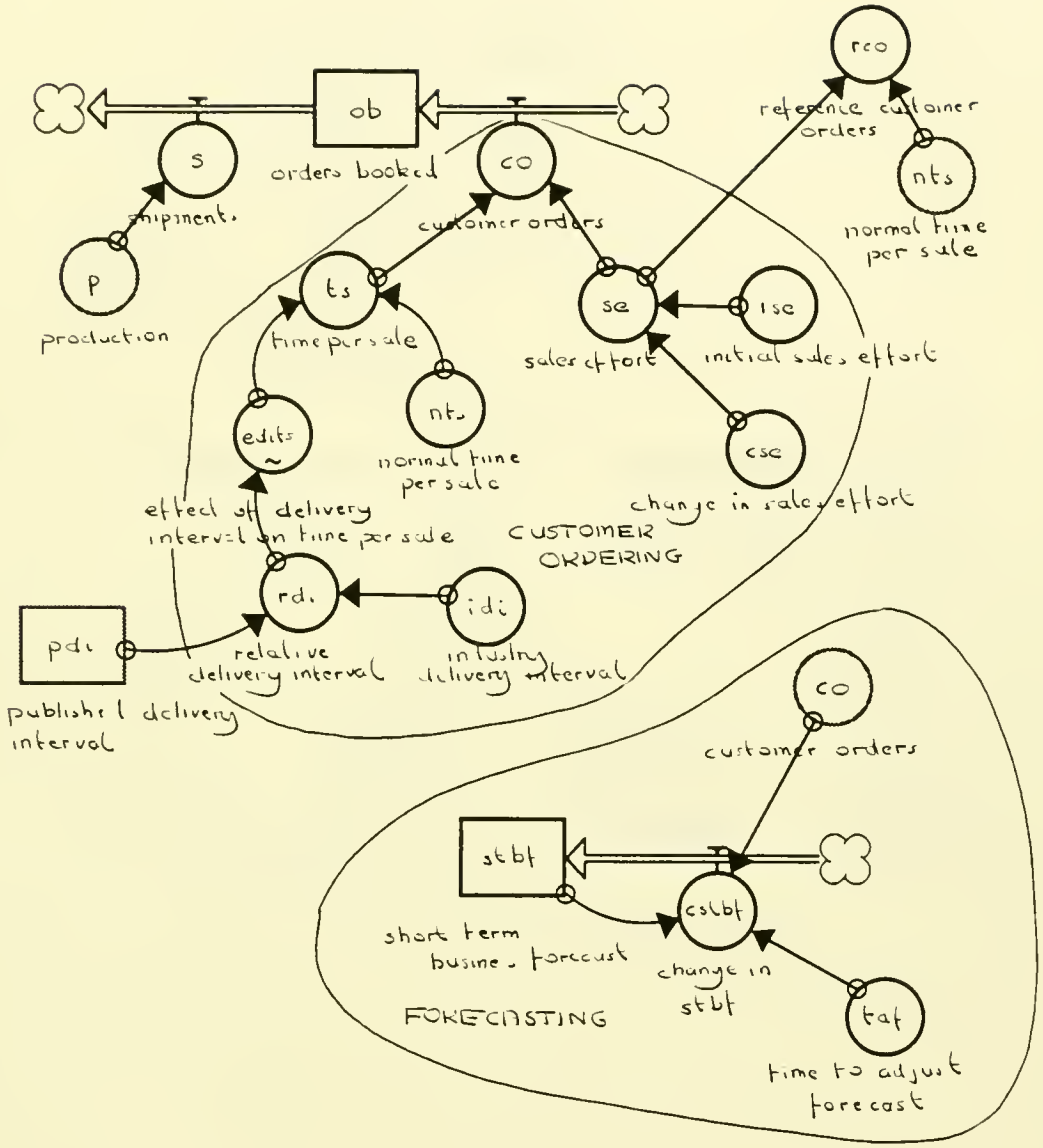

Figure 18: STELLA Diagram of Customer Ordering and Forecasting in the Base Sales and Production Scheduling Model (saps_base)

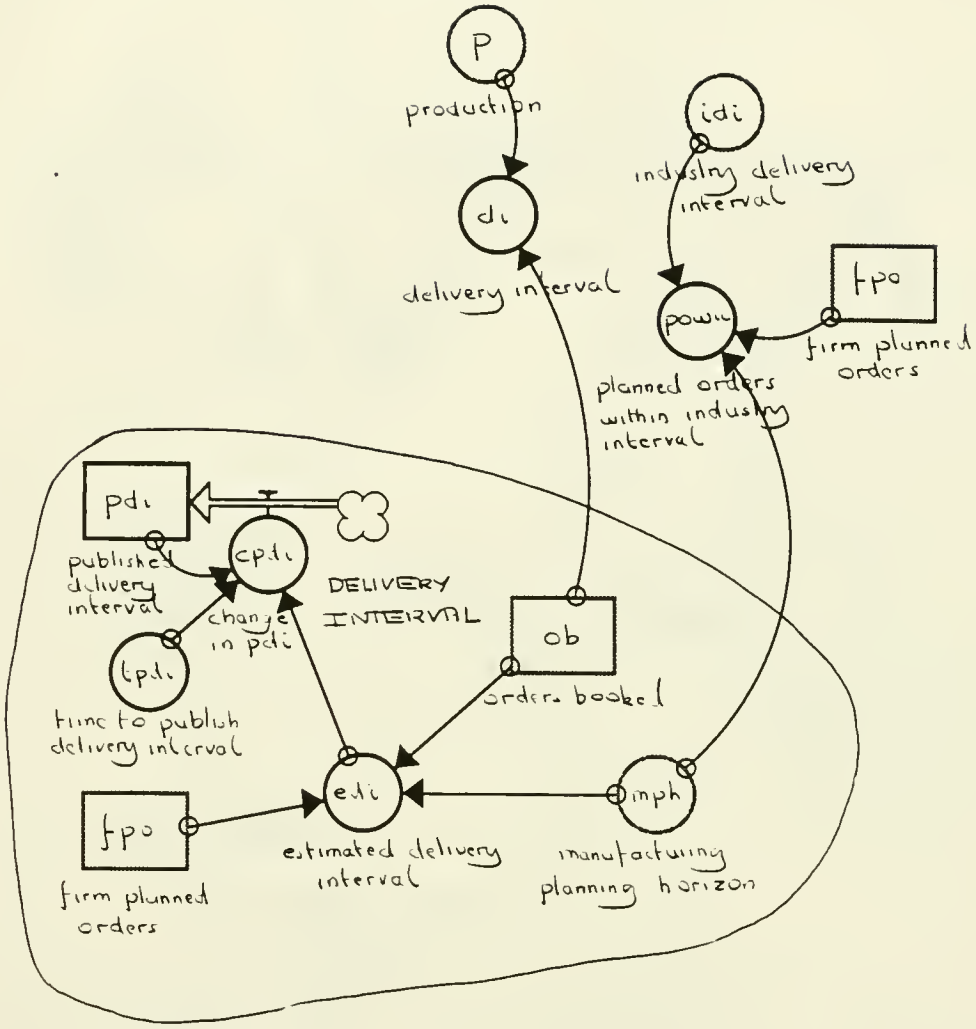

Figure 19: STELLA Diagram of Delivery Interval in the Base Sales and Production Scheduling Model (saps_base)

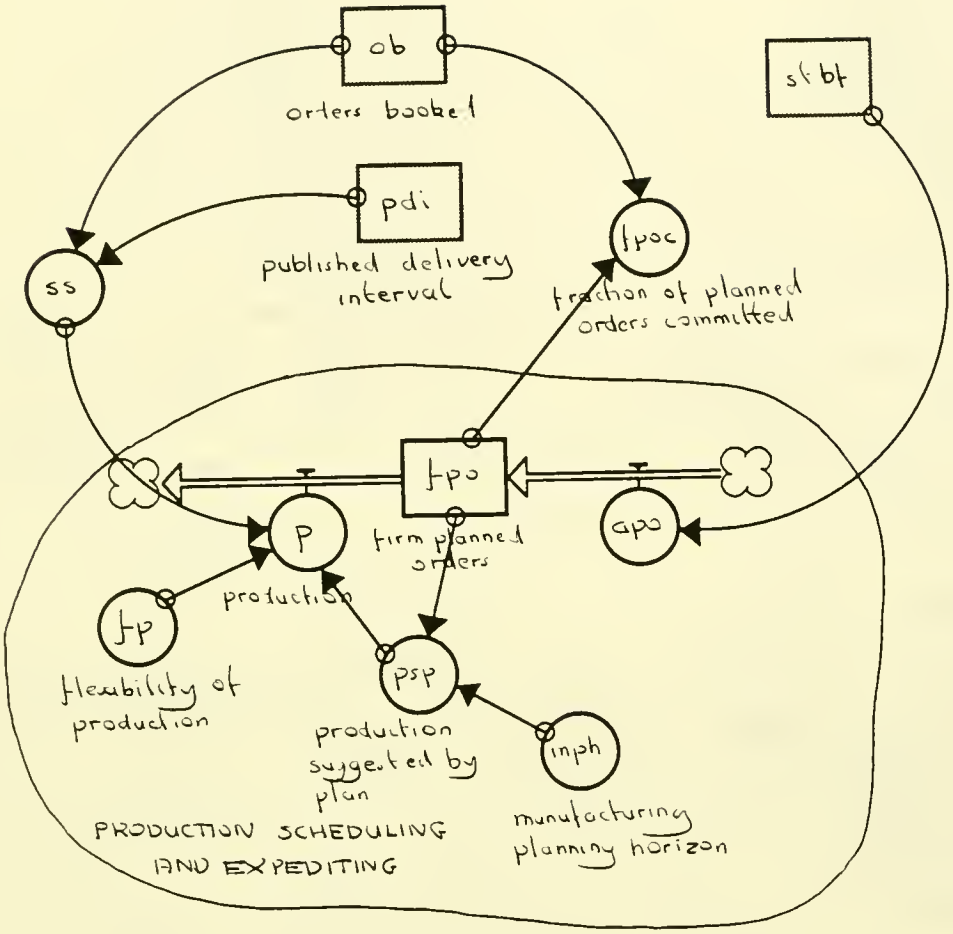

Figure 20: STELLA Diagram of Production Scheduling and Expediting in the Base Sales and Production Scheduling Model (saps_base)

```
fpo = fpo - p + apo
INIT(fpo) = stbf*mph
ob = ob + co - s
INIT(ob) = 300
pdi = pdi + cpdi
INIT(pdi) = idi
stbf = stbf + cstbf
INIT(stbf) = co
apo = stbf
co = se/ts
cpdi = (edi-pdi)/tpdi
cse = .2
cstbf = (co-stbf)/taf
di = ob/p
edi = (ob/fpo)*mph
fp = .3
fpoc = ob/fpo
idi = 3
ise = 7500
mph = 6
nts = 75
p = ss*fp+psp*(1-fp)
powii = fpo*(idi/mph)
psp = fpo/mph
rco = se/nts
rdi = pdi/idi
s = p
se = IF TIME <5 THEN ise ELSE (ise*(1+cse))
ss = ob/pdi
taf = 6
tpdi = 1
ts = nts*edits
```

```
edits = graph(rdi)
 0.0 -> 0.800
0.500 -> 0.850
1.000 -> 1.000
1.500 -> 1.150
2.000 -> 1.350
2.500 -> 1.550
3.000 -> 1.825
3.500 -> 2.150
4.000 -> 2.500
4.500 -> 2.900
5.000 -> 3.500
```

STELLA Equations for the Base Sales and Production Scheduling Model (saps_base)

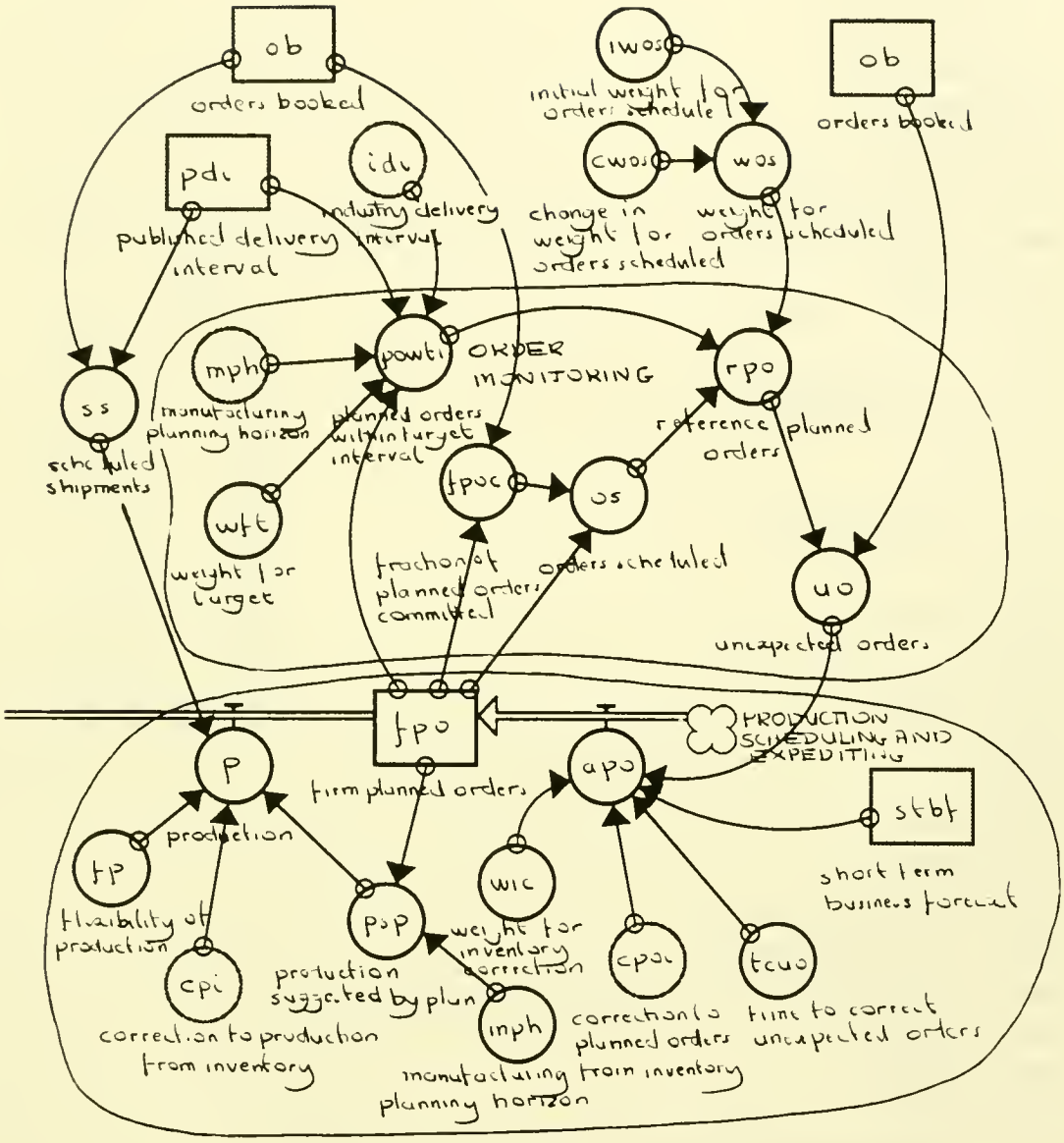

Figure 21: STELLA Diagram of Order Monitoring, Production Scheduling and Expediting in the Sales and Production Scheduling Model with Order Monitoring and Control (saps_ordmon)

```
fpo = fpo - p + apo
INIT(fpo) = stbf*mph
ob = ob + co - s
INIT(ob) = 300
pdi = pdi + cpdi
INIT(pdi) = idi
stbf = stbf + cstbf
INIT(stbf) = co
apo = stbf+(uo/tcuo)
co = se/ts
cpdi = (edi-pdi)/tpdi
cse = .2
cstbf = (co-stbf)/taf
cwos = 0
di = ob/p
edi = (ob/fpo)*mph
fp = .3
fpoc = ob/fpo
idi = 3
ise = 7500
iwos = 0
mph = 6
nts = 75
os = fpo*fpoc
p = ss*fp+psp*(1-fp)
powii = fpo*(idi/mph)
powti = fpo*(pdi/mph)*(1-wft)+fpo*(idi/mph)*wft
psp = fpo/mph
rco = se/nts
rdi = pdi/idi
rpo = os*wos+powti*(1-wos)
s = p
```

STELLA Equations for the Sales and Production Scheduling Model with Order Monitoring and Control (saps_ordmon)

```
se = IF TIME <5 THEN ise ELSE (ise*(1+cse))
ss = ob/pdi
taf = 6
tcuo = 1
tpdi = 1
ts = nts*edits
uo = ob-rpo
wft = 1
wos = IF TIME < 40 THEN iwos ELSE (iwos*(1+cwos))
edits = graph(rdi)
 0.0 -> 0.800
0.500 -> 0.850
1.000 -> 1.000
1.500 -> 1.150
2.000 -> 1.350
2.500 -> 1.550
3.000 -> 1.825
3.500 -> 2.150
4.000 -> 2.500
4.500 -> 2.900
5.000 -> 3.500
```

STELLA Equations Continued -- for the Sales and Production Scheduling Model with Order Monitoring and Control (saps_ordmon)

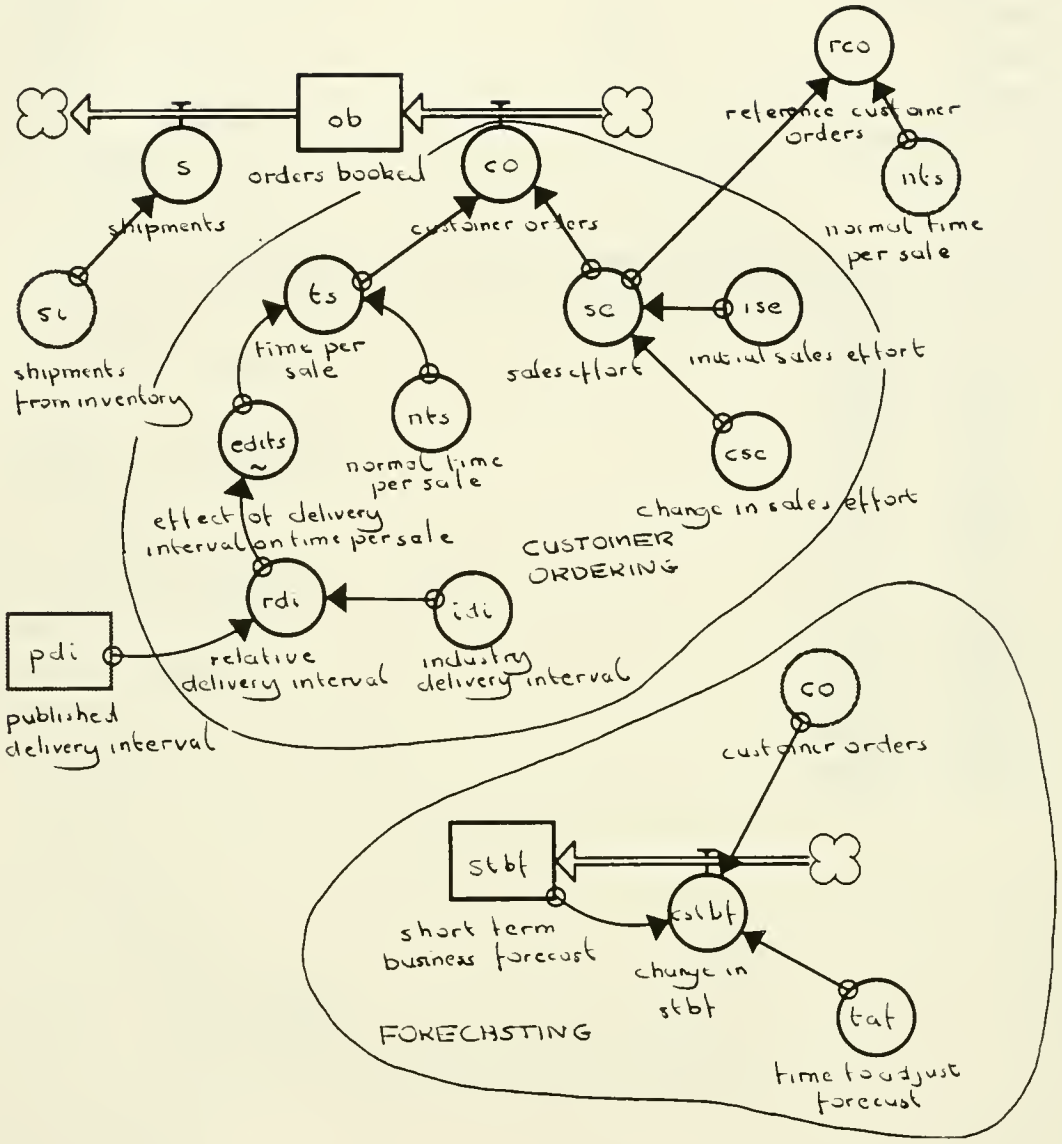

Figure 22: STELLA Diagram of Customer Ordering and Forecasting in the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

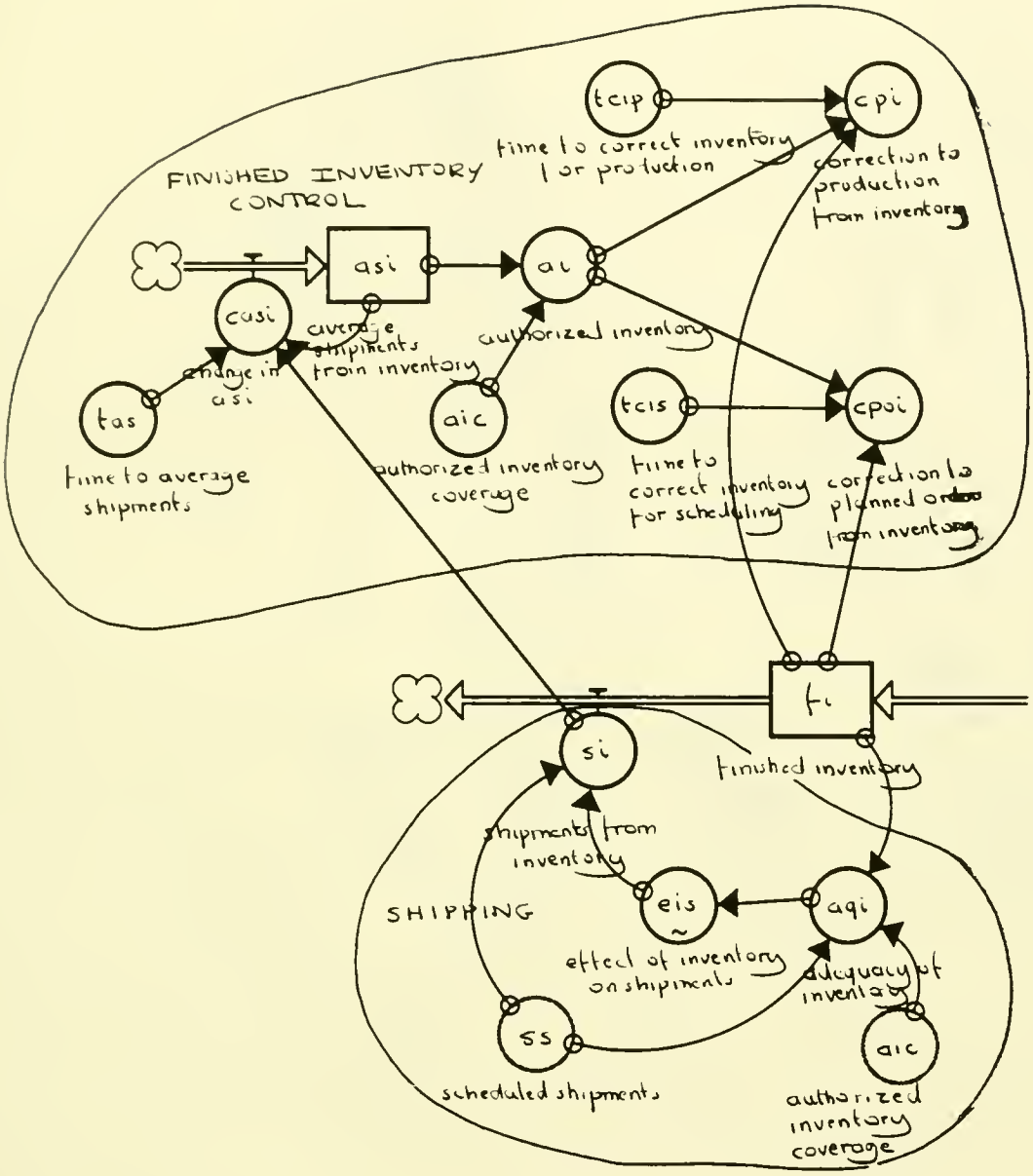

Figure 23: STELLA Diagram of Finished Inventory Control and Shipping in the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

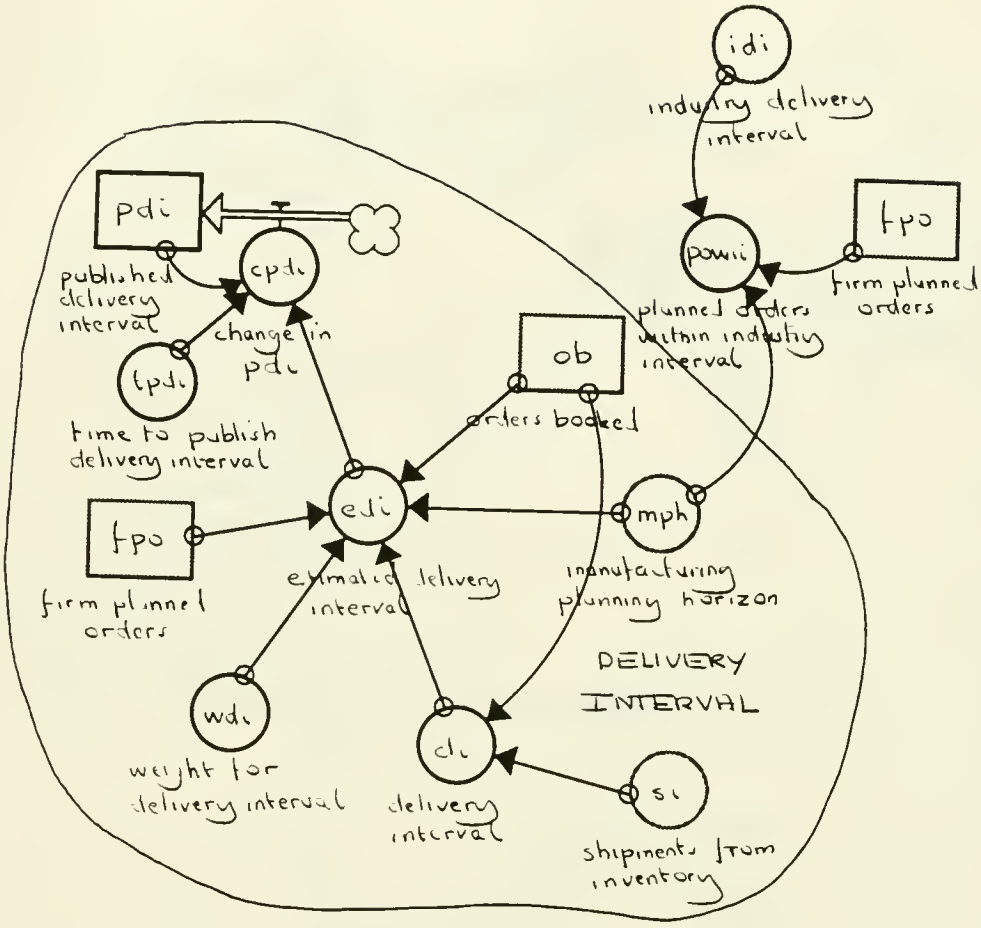

Figure 24: STELLA Diagram of Delivery Interval in the Sales and Production Scheduling Model with Finished Inventory Control (saps-invcon)

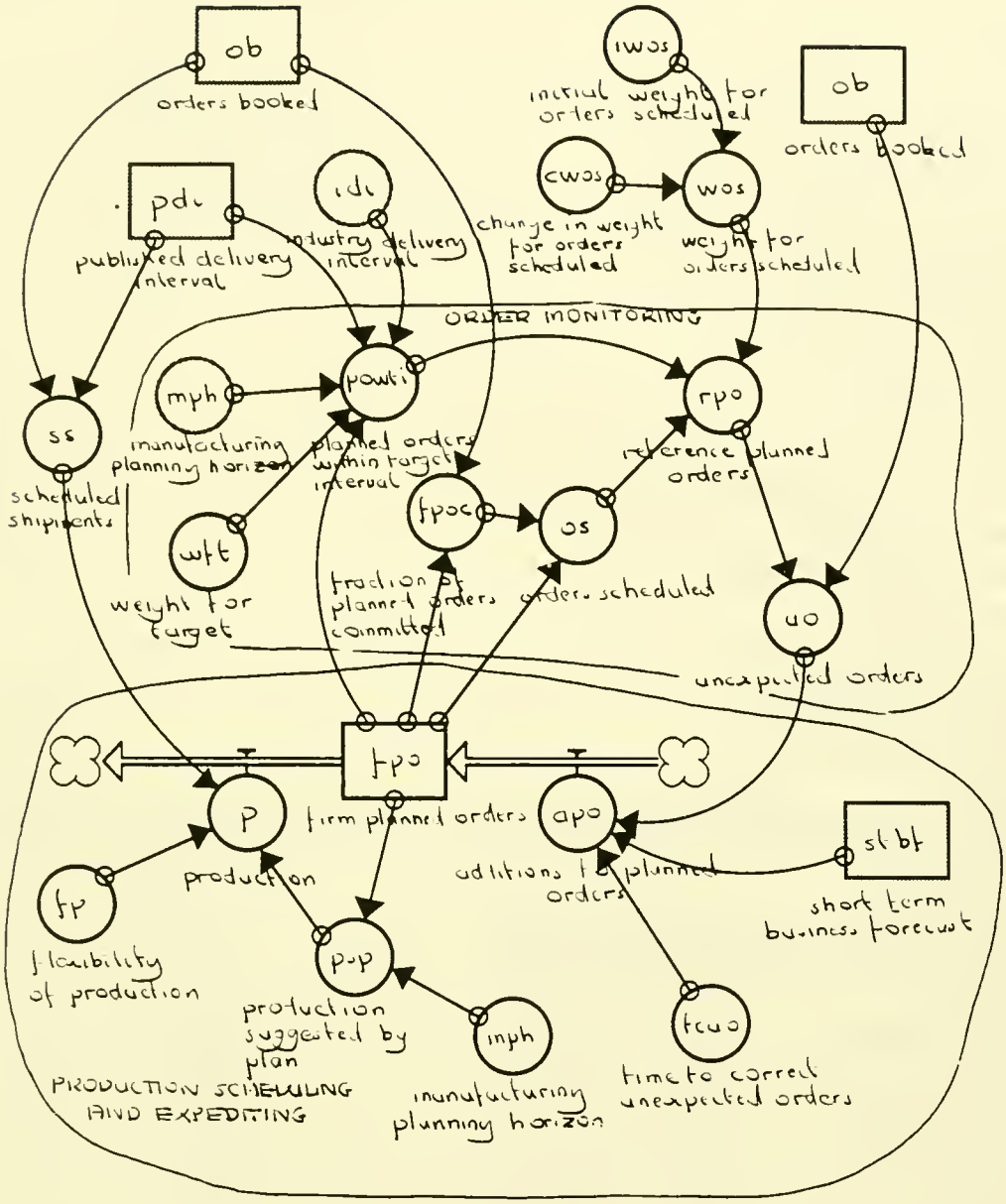

Figure 25: STELLA Diagram of Order Monitoring, Production Scheduling and Expediting in the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

```
asi = asi + casi
INIT(asi) = si
fi = fi + p - si
INIT(fi) = co*aic
fpo = fpo + apo - p
INIT(fpo) = stbf*mph
ob = ob + co - s
INIT(ob) = 300
pdi = pdi + cpdi
INIT(pdi) = idi
stbf = stbf + cstbf
INIT(stbf) = co
ai = asi*aic
aic = 3
apo = stbf+(uo/tcuo)+(cpoi*wic)
aqi = fi/(ss*aic)
casi = (si-asi)/tas
co = se/ts
cpdi = (edi-pdi)/tpdi
cpi = (ai-fi)/tcip
cpoi = (ai-fi)/tcis
cse = .2
cstbf = (co-stbf)/taf
cwos = 0
di = ob/si
edi = (ob/fpo)*mph*(1-wdi)+di*wdi
fp = .3
fpoc = ob/fpo
idi = 3
ise = 7500
iwos = 1
mph = 6
nts = 75
os = fpo*fpoc
```

STELLA Equations for the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

```
p = (ss+cpi)*fp+psp*(1-fp)
powii = fpo*(idi/mph)
powti = fpo*(pdi/mph)*(1-wft)+fpo*(idi/mph)*wft
psp = fpo/mph
rco = se/nts
rdi = pdi/idi
rpo = os*wos+powti*(1-wos)
s = si
se = IF TIME <5 THEN ise ELSE (ise*(1+cse))
si = ss*eis
ss = ob/pdi
taf = 6
tas = 12
tcip = 2
tcis = 2
tcuo = 1
tpdi = 1
ts = nts*edits
uo = ob-rpo
wdi = 1
wft = 0
wic = 1
wos = IF TIME < 40 THEN iwos ELSE (iwos*(1+cwos))
edits = graph(rdi)
 0.0 -> 0.800
0.500 -> 0.850
1.000 -> 1.000
1.500 -> 1.150
2.000 -> 1.350
2.500 -> 1.550
3.000 -> 1.825
3.500 -> 2.150
4.000 -> 2.500
4.500 -> 2.900
5.000 -> 3.500
eis = graph(aqi)
 0.0 ->  0.0
0.200 -> 0.950
0.400 -> 0.980
0.600 -> 1.000
0.800 -> 1.000
1.000 -> 1.000
1.200 -> 1.000
1.400 -> 1.000
1.600 -> 1.000
1.800 -> 1.000
2.000 -> 1.000
```

STELLA Equations Continued -- for the Sales and Production Scheduling Model with Finished Inventory Control (saps_invcon)

DEFINITION OF VARIABLE NAMES

ai	authorized inventory (systems)
aic	authorized inventory coverage (months)
apo	additions to planned orders (systems/month)
asi	average shipments from inventory (systems/month)
aqi	adequacy of inventory (dimensionless)
casi	change in average shipments from inventory (systems/month/month)
co	customer orders (orders for systems/month)
cpdi	change in perceived delivery interval (months/month)
cpi	correction to production from inventory (systems/month)
cpoi	correction to planned orders from inventory (systems/month)
cse	change in sales effort (dimensionless)
cstbf	change in short-term business forecast (systems/month/month)
cwos	change in weight for orders scheduled (dimensionless)
di	delivery interval (months)
edi	estimated delivery interval (months)
edits	effect of delivery interval on time per sale (dimensionless)
eis	effect of inventory on shipments (dimensionless)
fi	finished inventory (systems)
fp	flexibility of production (dimensionless)
fpo	firm planned orders (systems planned)
fpoc	fraction of planned orders committed (dimensionless)
idi	industry delivery interval (months)
ise	initial sales effort (hours/month)
iwos	initial weight for orders scheduled (dimensionless)
mph	manufacturing planning horizon (months)
nts	normal time per sale (hours/system)
ob	orders booked (orders for systems)
os	orders scheduled (systems planned)
p	production (systems/month)
pdi	published delivery interval (months)
powii	planned orders within industry interval (systems planned)

DEFINITION OF VARIABLE NAMES – CONTINUED

powti	planned orders within target interval (systems planned)
psp	production suggested by plan (systems/month)
rco	reference customer orders (orders for systems/month)
rdi	relative delivery interval (dimensionless)
rpo	reference planned orders (systems planned)
s	shipments (systems/month)
se	sales effort (hours/month)
si	shipments from inventory (systems/month)
ss	scheduled shipments (systems/month)
stbf	short-term business forecast (systems/month)
taf	time to adjust forecast (months)
tas	time to average shipments (months)
tcip	time to correct inventory for production (months)
tcis	time to correct inventory for schedule (months)
tcuo	time to correct unexpected orders (months)
tpdi	time to publish delivery interval (months)
ts	time per sale (hours/system)
uo	unexpected orders (orders for systems)
wdi	weight for delivery interval (dimensionless)
wft	weight for fixed target (dimensionless)
wic	weight for inventory correction (dimensionless)
wos	weight for orders scheduled (dimensionless)

DESCRIPTION OF PARAMETER AND STRUCTURAL CHANGES FOR SIMULATION SCENARIOS

Base Run (Model saps_base)

The base run is described on pages 15 through 19 of the report. The base run uses the model saps_base -- a version of the model in which there is no feedback to production planning from orders booked, and in which there is no finished inventory. The production plan (more specifically, additions to planned orders) is therefore equal to the forecast. The forecast is assumed to be an exponential smoothing of customer orders, with a smoothing constant (time to adjust the forecast taf) of 6 months.

Monitoring and Control of Excess Orders (model saps_ordmon)

The model saps_ordmon is the same as the base model, but with new equations to represent a policy of monitoring and control of excess orders. Simulations of the model are described on pages 20 through 24 of the report. The new equations are described below.

a). Additions to Planned Orders

0 apo = stbf + uo/tcuo	1
0 tcuo = 1	2

where:

apo	additions to planned orders (systems planned/month)
stbf	short-term business forecast (systems/month)
uo	unexpected orders (orders for systems)
tcuo	time to correct unexpected orders (months)

In the base model, the additions to planned orders (apo) are equal to the short-term business forecast (stbf). In other words, when planners add new production orders to the production schedule, they add the number of orders called for by the forecast (stbf). But, when they adopt the order monitoring and control policy they also add a proportion of the unexpected orders (uo) on top of the forecast. When the forecast is innaccurate, or more specifically, when it is biased downward, unexpected orders accummulate which are factored into the production plan as shown in equation 1.

b). Unexpected Orders

But what are unexpected orders and how do schedulers recognize them? Equations 3 through 9 show how.

```
0 uo = ob - rpo                                  3
0 rpo = os*wos + powti*(1-wos)                   4
0 os = fpo*fpoc                                  5
0 fpoc = ob/fpo                                  6
0 wos = 0                                        7
0 powti = fpo*(pdi/mph)*(1-wft)
          +fpo*(idi/mph)*wft                     8
0 wft = 1                                        9
```

where:

uo	unexpected orders (orders for systems)
ob	orders booked (orders for systems)
rpo	reference planned orders (systems)
os	orders scheduled (systems)
fpo	firm planned orders (systems)
fpoc	fraction of planned orders committed (dimensionless)

wos weight for orders scheduled (dimensionless)
powti planned orders within target interval (systems)
pdi published delivery interval (months)
idi industry delivery interval (months)
mph manufacturing planning horizon (months)
wft weight for fixed target (dimensionless)

The equations contain two switches -- weight for orders scheduled (wos) and weight for fixed target (wft) which allow one to make different assumptions about the effectiveness of the order monitoring and control policy. The simulations described in the report were obtained by setting wos = 0 and wft = 1 -- a combination of switches that results in very effective order monitoring and control. With this combination, the equation for reference planned orders (rpo) reduces to:

0 rpo = fpo*(idi/mph)

So, we are saying in equation 3 that schedulers recognize unexpected orders (uo) by comparing orders booked (ob) with reference planned orders (rpo), and that they take as their reference point only the planned orders scheduled for production within the industry's delivery interval (the quantity fpo*(idi/mph).

If the parameter, weight for orders scheduled (wos), is set to 1, then the model saps_ordmon becomes equivalent to the base model. Under this condition, the equation for reference planned orders (rpo) reduces to:

0 rpo = os

But, as equations 5 and 6 show, orders scheduled (os) are those planned orders that have been assigned to customer orders -- in other words, orders booked (ob)!! So, in equation 3, unexpected orders are always zero,

and in equation 1 additions to planned orders (apo) are equal to the short-term business forecast (stbf) -- the same assumption used in the base model. (One might ask, why take the trouble to write equations for reference planned orders (rpo) if the numerical value of reference planned orders (rpo) is zero. The answer is that the equations show the process by which schedulers and planners recognize excess orders -- the information they use to assess whether customers have ordered more than expected. It turns out that in a system where schedulers have the freedom to assign customer orders to any open production slot (a slot-planning system) it's difficult to recognize excess orders because, if the planning horizon is long enough, schedulers can always find open production slots).

Finished Inventory Control (model saps_invcon)

The model saps_invcon is the same as saps_ordmon, but with equations added to represent finished inventory, production for inventory, shipping from inventory (in saps_ordmon shipping is equal to production) and finished inventory control. The new equations are described below.

a). Finished Inventory and Shipping

```
□fi = fi + p - si                    1
INIT(fi) = co*aic                    2
0 si = ss*eis                        3
0 eis = graph(aqi)                   4
0 aqi = fi/(ss*aic)                  5
```

where:

fi	finished inventory (systems)
p	production (systems/month)
si	shipments from inventory (systems/month)
co	customer orders (orders for systems/month)
aic	authorized inventory coverage (months)
ss	scheduled shipments (systems/month)
eis	effect of inventory on shipments (dimensionless)
aqi	adequacy of inventory (dimensionless)

Equation 1 states that finished inventory (fi) is increased by production (p) and reduced by shipments from inventory (si). So production and shipments are no longer identical as they were in the base model and in saps_ordmon, but can move (somewhat) independently because they are separated by a level of inventory.

Equations 3 through 5 describe shipping. If there is adequate finished inventory then shipments from inventory (si) are equal to the shipping schedule (ss). The factory can ship according to schedule because there is adequate product available -- in other words, the effect of inventory on shipments (eis) is neutral (takes a numerical value of 1). The key to the success of the finished inventory control policy is for the factory to hold enough finished inventory that stockouts of high-volume items never occur. By preventing stockouts, the factory can maintain constant delivery intervals and so avoid the possibility of inadvertently suppressing customer orders. The following parameter values represent a no-stockout inventory in the model saps_invcon:

authorized inventory coverage aic = 3 months

effect of inventory on shipments eis = graph(aqi) such that when adequacy of inventory

aqi = 0	eis = 0
aqi = 0.2	eis = .95
aqi = 0.4	eis = .98
aqi = 0.6	eis = 1.0
aqi = 0.8	eis = 1.0
aqi = 1.0	eis = 1.0
aqi = 1.2	eis = 1.0
aqi = 1.4	eis = 1.0
aqi = 1.6	eis = 1.0
aqi = 1.8	eis = 1.0
aqi = 2.0	eis = 1.0

It is important that the effect of inventory on shipments (eis) remains at the value 1, or very close to 1, over a wide range of values of finished inventory, because then the factory is always able to ship acording to schedule. If you study the graph function for the effect of inventory on shipments you'll see that when adequacy of inventory is 1 -- when the factory's finished inventory is exactly equal to the authorized inventory, which is three months of shipments -- then the effect of inventory on shipments (eis) is also 1. When the adequacy of inventory (aqi) falls -- when the factory's inventory is less than authorized -- the effect of inventory on shipments (eis) stays very close to the value 1. Only when the adequacy of inventory reaches the value .2 -- when the factory's is only one fifth of the authorized -- does the effect of inventory on shipments start to decline rapidly, signifying that the factory is out-of-stock on

some product lines and therefore unable to ship according to schedule.

The reader should be aware that one cannot arbitrarily specify the shape of the effect of inventory on shipments (eis). The shape depends on the authorized inventory coverage (aic) and on the diversity of products the factory produces and holds in finished inventory. If the factory produces many different products then it should plan to hold a lot of finished inventory (in other words, the authorized inventory coverage will be high, say 3 or 4 months of shipments) to be sure of avoiding stock-outs, and therefore to be sure that the effect of inventory on shipments remains close to the value 1. On the other hand, if the factory produces only one product line, a stock-out can occur only when finished inventory is zero. So the effect of inventory on shipments (eis) will remain at the value 1 even if the factory's authorized inventory coverage (aic) is only one month or one week of shipments.

So, when using the model saps_invcon, it is important to think carefully about the shape of the effect of inventory on shipments (eis) -- how it changes depending on the factory's authorized inventory coverage (aic) and on the assumptions one makes about the factory's number of product lines. For example, if one were to rerun saps_invcon with authorized inventory coverage reduced to only one month, instead of three, (and with the assumption that the factory produces several, say 10, different product lines) then it would be essential to make the effect of inventory on

shipments (eis) slope more gradually upward from the (0,0) point. One would find that, the more gradual the slope, the less effective the inventory control policy would be in regulating delivery interval -- because the factory would stock-out more easily.

b). Finished Inventory Monitoring and Control

To use the finished inventory effectively for production planning, the factory's warehouse must monitor the difference between finished inventory and authorized inventory and report the difference to schedulers and planners. The schedulers and planners use the information to adjust both current production and the production plan. The equations to represent the monitoring and control of finished inventory are shown below:

$$0\ apo = stbf + (uo/tcuo) + (cpoi*wic) \qquad 6$$
$$0\ cpoi = (ai - fi)/tcis \qquad 7$$
$$0\ p = (ss + cpi)*fp + psp*(1-fp) \qquad 8$$
$$0\ cpi = (ai - fi)/tcip \qquad 9$$

where:

apo	additions to planned orders (systems/month)
stbf	short-term business forecast (systems/month)
uo	unexpected orders (orders for systems)
tcuo	time to correct unexpected orders (months)
cpoi	correction to planned orders from inventory (systems/month)
ai	authorized inventory (systems)
fi	finished inventory (systems)
tcis	time to correct inventory for scheduling (months)
p	production (systems/month)
ss	scheduled shipments (systems/month)

cpi	correction to production from inventory (systems/month)
fp	flexibility of production (dimensionless)
psp	production suggested by plan (systems/month)
tcip	time to correct inventory for production (months)

Equation 6 states that when planners make additions to planned orders they add to the short-term busines forecast (stbf) a correction to planned orders from finished inventory (cpoi). They make a correction whenever there is a reported difference between authorized inventory (ai) and finished inventory (fi) as shown in equation 7. (They also add to the short-term business forecast (stbf) a correction for unexpected orders (uo) -- but in the simulations shown in the report, unexpected orders are always zero because reference planned orders (rpo) are equal to orders scheduled (os)).

Equation 8 and 9 state that schedulers make a correction to production (cpi) based on the reported difference between authorized inventory (ai) and finished inventory (fi). If finished inventory (fi) is lower than authorized (ai) they add a portion of the difference to scheduled shipments in order to consume the schedule of planned orders more quickly and so re-build finished inventory.

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